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NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

**TROPICAL CYCLONE RECONNAISSANCE OVER THE
WESTERN NORTH PACIFIC WITH THE GLOBAL
HAWK: OPERATIONAL REQUIREMENTS, BENEFITS,
AND FEASIBILITY**

by

Robert E. Atkinson, III

September 2012

Thesis Advisor:
Second Reader:

Patrick A. Harr
Jeff Kline

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13. ABSTRACT (maximum 200 words) Over the North Atlantic Ocean, an operational manned aircraft-based tropical cyclone (TC) reconnaissance program is conducted by the United States Air Force. However, no such program is conducted over the western North Pacific (WPAC), where the maximum annual number of TCs occurs. Rather, remotely-sensed observations from satellites provide data on TC characteristics. While operational forecasts of TC track over the WPAC have improved, the rate of improvement has declined, and no such decline has been observed over the North Atlantic. In this study, the declining rate of improvement in WPAC forecast accuracy is examined relative to the lack of direct observations. The capabilities of manned-aircraft are compared with use of a Global Hawk unmanned aerial system for use as an observing platform. This is proposed in view of a declining capability in satellite data coverage. Current Global Hawk programs are reviewed with respect to requirements for operational tropical cyclone reconnaissance over the western North Pacific. A multi-year demonstration project is proposed to obtain in situ observations of TC location and intensity. The observation impacts on improved tropical cyclone forecasts will be assessed such that a positive impact will lead to recommendation of a Global Hawk for operational tropical cyclone reconnaissance.				
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**TROPICAL CYCLONE RECONNAISSANCE OVER THE WESTERN NORTH
PACIFIC WITH THE GLOBAL HAWK: OPERATIONAL REQUIREMENTS,
BENEFITS, AND FEASIBILITY**

Robert E. Atkinson
Lieutenant Commander, United States Navy
B.A., North Carolina State University, 2002

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN METEOROLOGY AND OCEANOGRAPHY

from the

**NAVAL POSTGRADUATE SCHOOL
September 2012**

Author: Robert E. Atkinson

Approved by: Patrick A. Harr
Thesis Advisor

Jeff Kline
Second Reader

Wendell A. Nuss
Chair, Department of Meteorology

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ABSTRACT

Over the North Atlantic Ocean, tropical cyclone (TC) reconnaissance is conducted by manned aircraft. However, over the western North Pacific (WPAC), where the climatological maximum annual number of TCs occurs, no aircraft reconnaissance is conducted. While the operational forecasts of TC motion has improved steadily over the past 40 years, there has been a decline in the rate of improvement. Over the North Atlantic, no such decline has been observed. In this study, it is shown that the decline in rate of improvement of forecast accuracy over the WPAC is related to the lack of *in situ* observations.

The capabilities of manned-aircraft reconnaissance are compared with the use of a Global Hawk unmanned aerial system for use as an observing platform. This is proposed in view of current projections of a rapidly-declining capability in satellite data coverage. Current Global Hawk programs, instrumentation, communications, and costs are reviewed with respect to required capabilities for an operational TC reconnaissance program over the WPAC. A multi-year demonstration project is proposed to obtain *in situ* observations of tropical cyclone location and intensity. Provided that a positive impact is achieved, the use of a Global Hawk for operational TC reconnaissance is recommended.

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I. INTRODUCTION

A. MOTIVATION

Tropical cyclones (TCs) are one of the most destructive of all weather phenomena. These storms present severe weather challenges that are a clear danger to Navy and Air Force ground operations in the U.S. Pacific Command (USPACOM) area of responsibility. In a climatological sense, the western North Pacific (WPAC) contains 31 TCs per year, which is the largest number of storms for any ocean basin. In support of Department of Defense (DoD) activity in the TC-active basin, the Joint Typhoon Warning Center (JTWC) is tasked with providing operational forecasts of TC formation, motion, and intensity.

A primary operational goal of the JTWC is to minimize the amount of area that must be placed under warning and maximize accuracy of forecast conditions. Forecast uncertainty can lead to an area being placed under warning that is larger than required. When warning areas are larger than necessary, geographic maneuverability is reduced, ship diversions and sorties may be undertaken when not needed, and shore-based installations may take protective action for time periods longer than required. Because of such impacts, USPACOM has identified tropical cyclone reconnaissance as one of its most important theatre security tools (Schultz, 2009). The ability to forecast TC formation and intensity is of critical importance to the safety and use of many national assets.

Forecasts of tropical cyclone characteristics are based upon a collection of observations and guidance from numerical weather prediction (NWP) models. Over the WPAC, *in situ* observations of TC characteristics are often obtained by ship, and land stations. These observations are not very common due to the hazardous conditions that accompany the TC. Remotely-sensed observations are obtained from a variety of geosynchronous and polar-orbiting satellites. The relative merits and limitations of these observation types will be discussed later.

The operational NWP models integrate the basic mathematical equations that govern atmosphere-ocean dynamic and thermodynamic properties as an initial-value problem. As such, the atmosphere is a chaotic system (Lorenz 1963) in which integration of the basic equation set exhibits a sensitivity to initial conditions. The quality of the initial conditions used to initialize the model is a key factor that influences the model-produced forecast. Therefore, improved initial conditions can lead to increased accuracy in numerical guidance, which often reduces forecast uncertainty and enables forecasters to reduce the area of potential impacts with increased confidence.

The initial conditions for a NWP model are created by using the short-range forecast as the basis for the analysis (Figure 1). The premise of this strategy is that the short-range (i.e., 3-h or 6-h) forecast is a first guess of the true state of the atmosphere at any given time. Small corrections are made to the first guess using information from new observations (Figure 1) such that it reflects the current state of the atmosphere. This process of updating a first guess of the atmospheric state using current observations is defined as data assimilation.

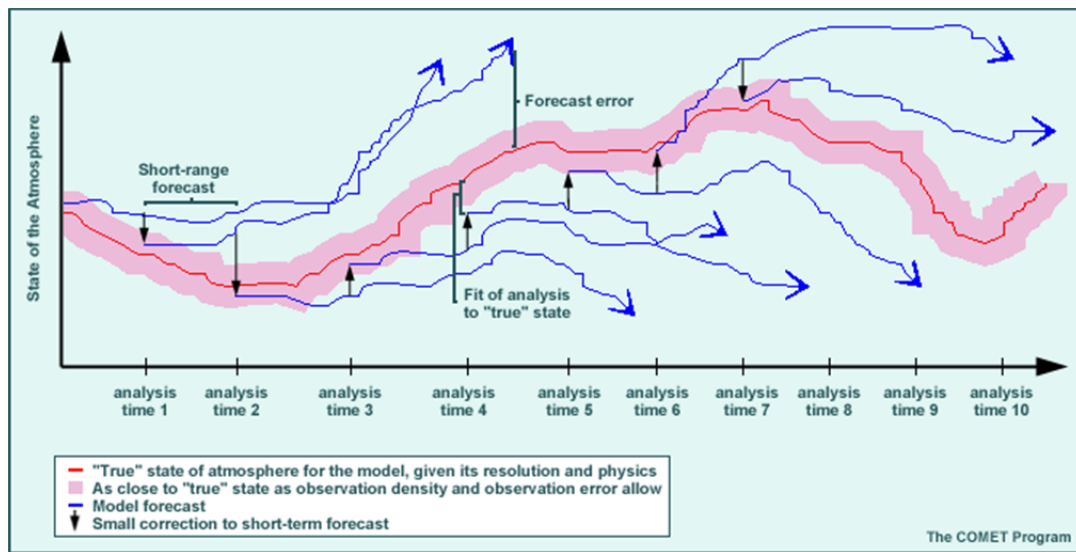


Figure 1. Schematic that defines how weather prediction models adjust short-range forecasts after observations are collected. [The COMET Program: Understanding Assimilation System: How Models Create Their Initial Conditions–version 2]

A first-order approximation for TC track forecasting is that the storm moves in response to the forcing by the large-scale environmental flow in which the storm is embedded. However, observed storm motion often deviates by some angle from the flow defined by the large-scale environment (Holland, 1983). The deviation from the environmental flow is due to the interaction between the storm and environment. To adequately address these processes in a numerical model, accurate initial conditions of both the environment and the storm structure are required. Because of the lack of *in situ* data in the region of a tropical cyclone, the data assimilation may not alter the first guess of the true state of the atmosphere in and near the TC. This may result in less accurate initial conditions if the model solutions tend to drift from the true state over time. Therefore, synthetic observations are defined to provide the data assimilation system with information to represent the TC in the initial condition. The synthetic observations are based on an assumed storm structure for a given intensity (Goerss, 2009). Often, the assumed storm structure used to construct the synthetic observations is quite different than the actual storm structure (Wu et al. 2012). Because TC tracks are related to the interaction between the storm and the environment in which it is moving, an incorrect representation of the storm structure often leads to erroneous environmental interactions and tracks (Jones et al. 2003; Harr et al. 2008, Wu et al., 2012).

Although geosynchronous satellites provide continuous coverage over TCs, the data characteristics do not provide an optimum level of information (i.e., three-dimensional depiction of winds, mass, and temperature) to define the structure of the TC or near environment adequately. Although depiction of the three-dimensional storm structure is required to properly initialize a numerical model, observations of the weather elements (i.e., winds, ocean waves) at the surface are crucial for the understanding and monitoring of hazardous weather conditions that impact shore-based and maritime operations. Again, direct measurements of surface weather elements are limited due to the extreme condition associated with a TC. Remotely-sensed observations of surface winds and ocean waves are possible from instruments mounted on polar-orbiting satellites. However, the number of crucial satellite platforms has been drastically reduced due to satellite life cycles and lack of replacements. Additionally, the uncertainty in

satellite-based observations can be large. The uncertainty in accuracy lowers the value of these observations to data assimilation for specification of initial conditions for numerical model integrations. For example, surface wind measurements made from passive microwave emission from the ocean surface can be highly influenced by high rain rates, which commonly occur during TC conditions.

It is clear that accurate forecast of TC characteristics depend on a variety of factors. A common aspect is that at the time that a forecast is initiated, accurate knowledge and depiction of the current storm characteristics and large-scale environment are critical to specifying accurate initial conditions upon which a forecast may be based. In this thesis, the sources, capabilities, and availability of current observing systems are examined with respect to TCs over the WPAC. The current capabilities are examined with reference to projected future assets.

It is hypothesized that addition of *in situ* observations in and near a TC over the WPAC will provide improved knowledge of current storm characteristics and improved initial conditions for model-generated forecast. As a basis for this hypothesis, special aircraft-based observations are examined for evidence that the observations may contribute to improved forecast accuracy. Based on these results, an unmanned aircraft, the Global Hawk, is examined as an observing platform for collection of *in situ* observation in the environment of a TC. This strategy is examined in relation to current Global Hawk capabilities, use, and availability over the WPAC.

While the sensitivity to initial conditions can be a limitation to predictability, it can be used to identify regions where small errors in the initial conditions will lead to rapidly growing errors in the time integrations (Reynolds et al., 2007, 2009). Identification of these regions is routinely done at most worldwide operational numerical weather prediction centers. Ideally, observations would be targeted in these regions to reduce the uncertainty in the initial conditions and thus reduce the growth of errors in the time integration (i.e., forecasts). Over the North Atlantic, targeted observations are obtained by operational aircraft reconnaissance. Unfortunately, in the western North Pacific, observational resources are not usually available or in the form such that they can be adapted to varying temporal, horizontal, and vertical requirements. Results from past

experiments have indicated that forecast accuracy of tropical cyclone tracks is increased when an increased number of observations in the environment of a tropical cyclone are obtained by manned aircraft, and then utilized to define a more accurate set of initial conditions for numerical integration (Harnisch and Weissmann 2010, Weissmann et al. 2011). The primary objective of this study is to define a framework in which an increased capability for observations of the near-tropical cyclone environment could be defined using the Global Hawk aircraft over the western North Pacific.

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II. BACKGROUND

A. RECENT FORECAST SKILL OVER THE WESTERN NORTH PACIFIC

For nearly 40 years, the average track error of forecasts provided by JTWC has declined (Figure 2). Additionally, the rate of decline can be categorized into three periods that have direct correspondence to research, numerical modeling, and computational power. As mentioned above, early forecast methods concentrated on recognition of the environmental flow pattern surrounding a TC. That flow pattern was used to extrapolate a future TC position. Due to improvement in depicting environmental flow, and increased use of satellite data, a steady increase in forecast accuracy was achieved between 1974–1995 (Figure 2).

During the late 1980s and the early 1990s, concentrated research programs were conducted to study TC motion. Although forecast errors were declining, the rate of forecast decline was only near 1%. Also, each typhoon season would contain significant events in which large errors occurred (Chan 1986). Often, these cases would have significant impact on shore-based and maritime activities throughout the WPAC. Initial research results indicated that TC motion often deviated from an environmental-based vector, and the deviation was quite systematic. The deviation from steering was found to be related to the interaction between a TC and its environment (Holland, 1983). Prior to 1987, aircraft reconnaissance was conducted in and around TCs over the WPAC. This program provided real-time observations of the storm location, intensity, size, and strength. These parameters were used by forecasters as initial conditions upon which to base their forecast. Unfortunately, the aircraft reconnaissance program over the WPAC was ended in 1987 due to budgetary constraints. Over the ensuing 25 years, the sole provision of TC observations has come from satellites.

The increase in the rate of JTWC forecast improvement beyond 1995 may be attributed to several factors. Increased understanding of the interaction between the TC and its environment contributed to improved awareness of possible deviation from steering (Goerss, et al 2004). An increase in the capability and accuracy of operational

numerical models improved the key guidance to operational forecasters. A rapid increase in coverage from polar-orbiting satellites provided many new remote-sensing products. A significant research effort began to utilize new microwave imaging capabilities on the polar-orbiting satellites to provide measurements of storm structure and location (Goerss 2009). However, these measurements are only available when the satellite passes close to the TC. Many polar-orbiting satellites have exceeded their life expectancy, and currently, in the U.S., there are no existing programs aimed at replacing existing satellite systems (Figure 3). Geostationary satellites are fixed at global locations and provide imagery at intervals that average every 30 minutes. During daylight, visible images are available. At all times, infrared imagery of cloud-top and surface temperature are available. Additionally, images of water vapor are available at all times. Because of the spatial and temporal resolution, geostationary imagery are used to provide cloud-tracked winds based on the movement of cloud elements between successive images. While geostationary satellites provide high temporal resolution and spatial coverage of the entire ocean basin, visible, infrared, and water vapor data are coarse in the vertical. Therefore, a high degree of uncertainty in the vertical distribution of measurements for geostationary data reduce the value of the observation to data assimilation.

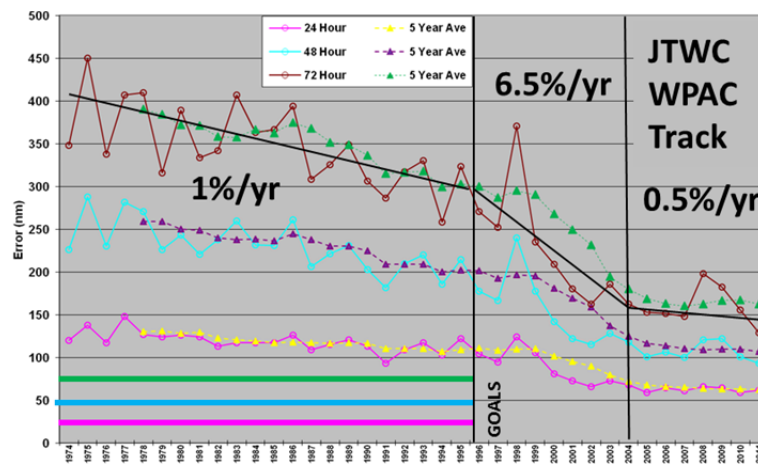


Figure 2. Average JTWC forecast error of TC track from 1974–2011. Percentages define the rates of improvement. (Dr. Peter Black, Naval Research Laboratory, 2012)

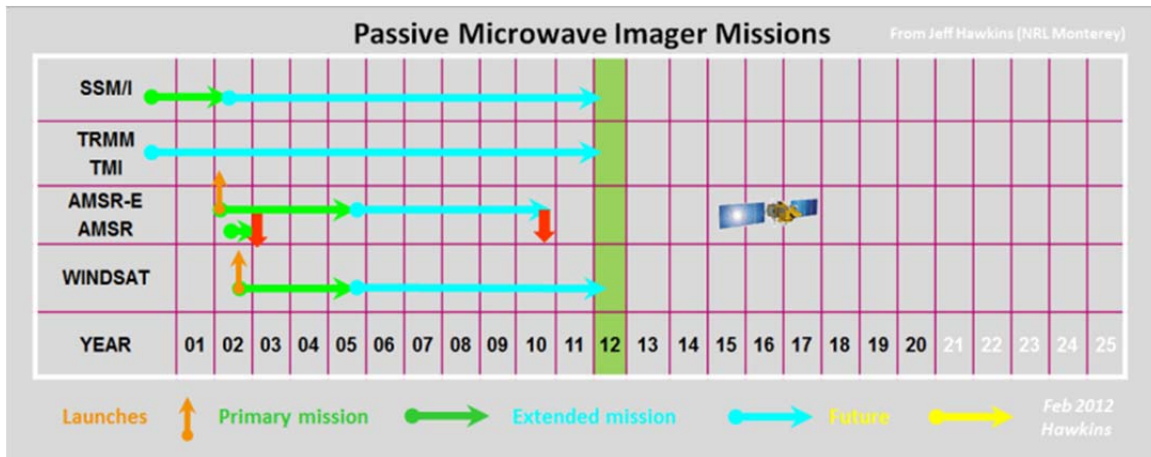


Figure 3. Summary of passive microwave imager sensors launched, in operations now, or recently failed. All future satellites are tentatively listed until actual launch occurs. Launch dates are subject to change at anytime and might be delayed for multiple years. (Naval Research Laboratory, Marine Meteorology Division, Monterey, CA Satellite Meteorology Applications Section)

After 2004, forecast errors have only declined slightly. While no one specific factor may be identified as responsible for the change in forecast accuracy, several factors may have contributed. One possibility is that the use and value of satellite data may have reached a plateau until new products become available (i.e., exploitation of new sensing channels, nighttime visible imagery). While satellite data coverage had reached an all-time maximum near 2008, there has been a sharp decline in recent years, which will be discussed below. A second factor is that the rate of improvement in numerical model forecast accuracy has also declined. Therefore, guidance to operational forecasts may not be improving at such a rate as realized during 1995–2004. Finally, a factor may be that there is an inherent limit to the predictability of TC motion over the WPAC.

While there has been a decrease in forecast track errors, there has been no corresponding decline in forecast intensity error over the WPAC (Figure 4). There are several possible reasons for the lack of improvement in intensity forecasts. One is an incomplete understanding of the primary processes that are internal to the TC and can impact the distribution of deep convection and strong winds. Over the recent five years,

dedicated research programs have been initiated to improve understanding of processes related to changes in TC intensity. A key aspect to these programs is the ability to obtain observations of storm-scale processes.

Over the Atlantic, the rate of improvement in TC track forecasts by the NHC has steadily improved for 20 years (Figure 5). Over the Atlantic, the rate of improvement in forecast accuracy has not fluctuated as it has over the Pacific (Figure 2). This may be due to differences in the environment of the two ocean basins. However, it may also be due to the timely *in situ* observations of storm location, structure, and intensity that are obtained over the Atlantic, by routine aircraft reconnaissance.

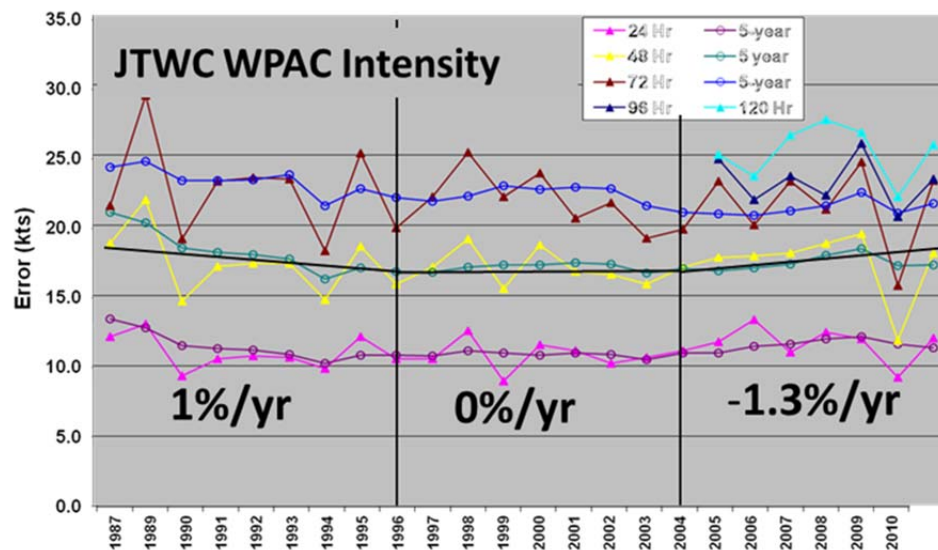


Figure 4. Average JTWC forecast errors for TC intensity from 1987–2011. Percentages define the rates of improvement. (Dr. Peter Black, Naval Research Laboratory, 2012)

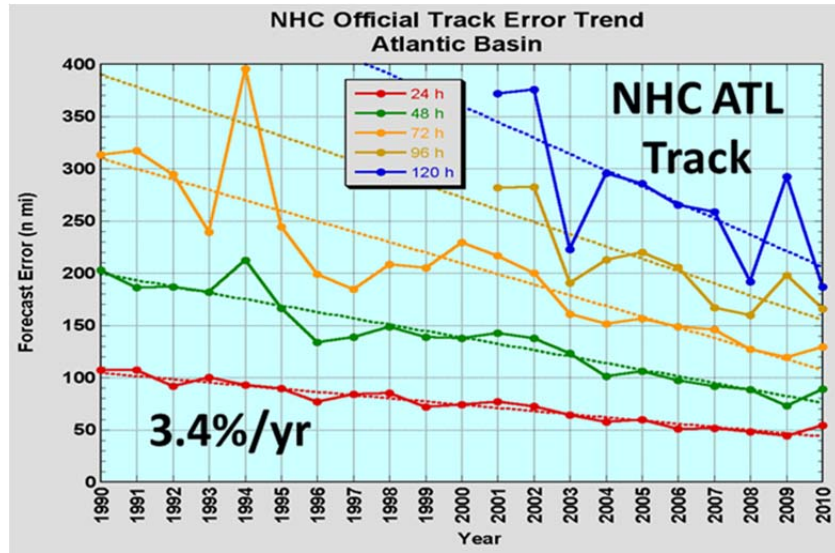


Figure 5. Average NHC forecast errors for TC intensity from 1990–2010. Percentages define the overall rate of improvement. (Dr. Peter Black, Naval Research Laboratory, 2012)

Although the improvement in TC track forecast accuracy over the Atlantic has improved relative to the WPAC, intensity forecasts have not improved (Figure 6). Again, this is likely related to a lack of understanding of basic physical processes that impact TC intensity. While operational reconnaissance has ended over the WPAC, manned aircraft from the National Atmospheric and Oceanic Administration (NOAA) and the USAF 53rd Weather Reconnaissance Squadron fly reconnaissance missions over the Atlantic, Caribbean and eastern North Pacific regions. In addition to the manned aircraft, some limited experimental use of unmanned aerial vehicles (UAV's) has obtained data at various levels of a TC. These are discussed more fully in Chapter III.

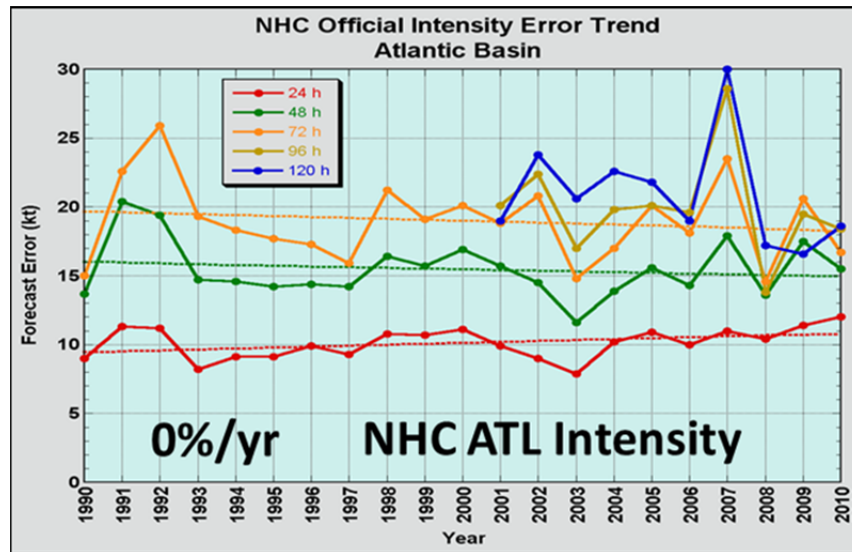


Figure 6. Average NHC forecast errors for TC intensity from 1990–2010. Percentage defines the overall rate of improvement. (Dr. Peter Black, Naval Research Laboratory, 2012)

Physical processes that are key with respect to understanding and forecasting of TC intensity occur at the lowest levels of the storm where energy is transferred from the ocean to the atmosphere. Because it is not possible to fly a manned aircraft in this harsh environment, this region is sampled using dropwindsondes and remote sensing from a flight level of 10,000 ft. There have been attempts made to operate small unmanned aerial vehicles (UAVs) in this environment (Lin, 2006, Lin and Lee 2008). In these and other experiments, the low-flying UAV has been successfully flown into tropical storms and hurricanes at an altitude of 300 feet (Darack, 2012).

Some scientists have noted the importance of the interaction between the TC outflow and the storm intensity (Emanuel, 2007). Typical levels of storm outflow are above 50,000ft. While a limited set of observations were obtained by a special flight of a NASA ER-2 (Halverson, et. al, 2006), observations at outflow level are not possible in operational reconnaissance programs, as this level is above the capability of aircraft currently used in operations.

B. OPERATIONAL FORECAST AIDS

1. Statistical

In 2002, the JTWC began using the Statistical Typhoon Intensity Prediction Scheme (STIPS) as an aid to intensity forecasting of tropical cyclones (Knaff, et al., 2005). This statistical model continues to be updated, and has increased in skill for most forecast times through 4 days (Knaff, et al., 2005). Unfortunately, the STIPS has not exhibited any forecast skill in predicting extreme cases of intensification rates greater than 25 kt d^{-1} . One of the reasons hypothesized for this lack of skill is because STIPS incorporates environmental conditions surrounding the storm rather than factors associated with the near-core convective region (Knaff, et al., 2005). Over the Atlantic basin, the equivalent Statistical Hurricane Integration Prediction System (SHIPS) is used as a primary forecast aid to the National Hurricane Center (NHC). The reference storm intensity that is used to initialize SHIPS is often based on *in situ* measurements obtained by aircraft reconnaissance. However, over the WPAC where aircraft are not available to provide *in situ* measurements of current storm intensity, the reference for STIPS is derived from satellite-based estimates of storm intensity. This may introduce an error in the initial conditions used in the statistical processing incorporated into STIPS.

2. Numerical

Operational forecasts of TC intensity and track are often based on predictions derived from operational numerical weather prediction models. These models integrate the set of fluid dynamical equations used to simulate the myriad of physical processes that occur in the TC and its environment. As an initial-value problem, observations are used to blend information on the current state of the atmosphere with a model-generated first guess of the atmospheric state (Figure 7). If the observation is not accurate, then the initial conditions may lead to reduced forecast accuracy or increased uncertainty. Information ahead of a storm gives an idea of what can be expected, but as the conditions change, the validity of that observation becomes less dependable. In the data sparse regions, synthetic observations or those from satellites are used, with less certainty.

Because of the relationship between the observations and model integration, *in situ* data are hypothesized to provide the best information to define initial conditions.

The process of generating a model initial condition is defined by Figure 8. The input variables in panel 1B are defined by observations. These may represent sea-surface temperature (SST), precipitation, wind speed, etc.. How the information gets into the model is represented by the arrows that lead from the observation to the forecast model. This data assimilation process can vary among models. The data assimilation process controls the influence of observations on the first guess such that accurate initial conditions are produced.

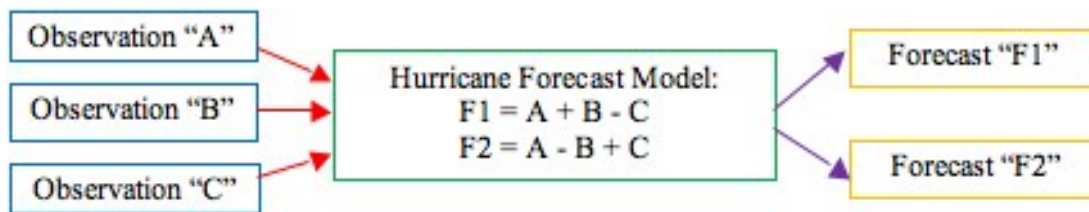


Figure 7. Schematic of the three components that define a numerical forecast model.
[www.hurricanescience.org/science/forecast/models/modelswork/]

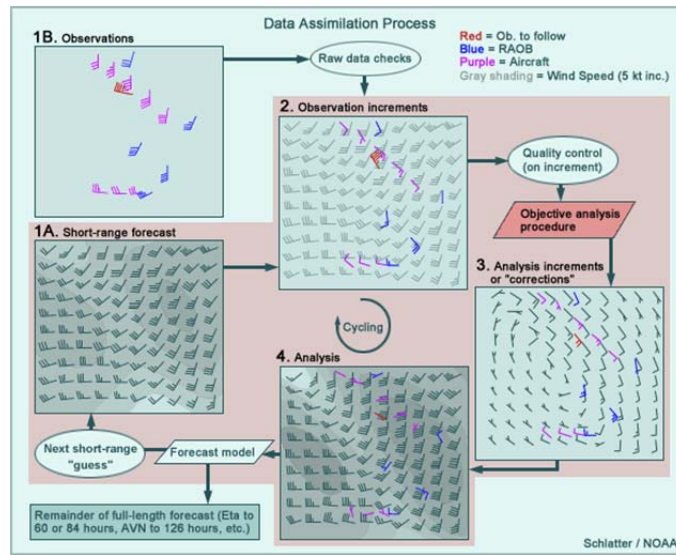


Figure 8. Data Assimilation Process. [COMET Module. Comet.ucar.edu]

Observations are taken from various platforms that include satellite, aircraft, ships and land station. These observations are considered raw data and whether the observation is accepted or rejected by the data assimilation system depends on the quality of the observation type. The data quality is related to the accuracy at which the instrument can measure atmospheric parameters. The observation increment is the increment or difference between the first guess and the noted observation. The analysis increments are the corrections to the first guess after summing the influences of all of the observations. The resulting analysis is the adjusted short-range forecast.

Because of the chaotic nature of the atmosphere, uncertainty will always exist in model solutions (Lorenz, 1963). To provide an estimate of forecast uncertainties, ensemble forecast models are generated by applying random perturbations to initial conditions. The dispersion in solutions contained in the ensemble is a measure of the uncertainty in a forecast due to sensitivities to initial conditions. The forecast model will always be highly dependent on the initial condition. Because of this relationship, improving the quality of the initial conditions can lead to increased forecast accuracy.

C. LIMITATIONS TO IMPROVED FORECASTS

Results from past experiments have indicated that forecast accuracy of tropical cyclone tracks is increased when an increased number of observations in the environment of a tropical cyclone are obtained by manned aircraft and then utilized to define a more accurate set of initial conditions for numerical integration (Harnisch and Weissmann 2010, Weissmann et al. 2011). In an effort to improve forecasts, targeted observations have been used to help reduce uncertainties of initial conditions in and near the TC. Ideally, observations are *targeted* to be placed in pre-defined regions to reduce the growth of errors in the time integration (i.e., forecasts) (Reynolds, et al., 2007). Primarily, these manned aircraft are used to obtain targeted observations over the North Atlantic. However, experiments have been conducted such that satellite data was used as targeted observations (Berger et. al., 2009). Whereas satellite-based observations are available over the WPAC, use of manned aircraft to obtain targeted observations is limited to special field programs.

Independent of the geographical region, another limitation to improving forecast accuracy is the acquisition of observation for long time periods and from higher levels in the vertical. During exercises and missions to study the formation of storms, manned aircraft are limited by the time spent in the air and the heights at which they can fly to cover the storm. During operational reconnaissance missions the WC-130J initially flies at an altitude of 500–1500 ft above the surface, to collect ocean data. Following these flight legs, the aircraft obtains atmospheric measurement at a typical altitude of 10,000 ft. Without the ability to refuel while in the storm, reconnaissance missions are limited in time such that the number of times a pattern (Figure 9) may be repeated is two.

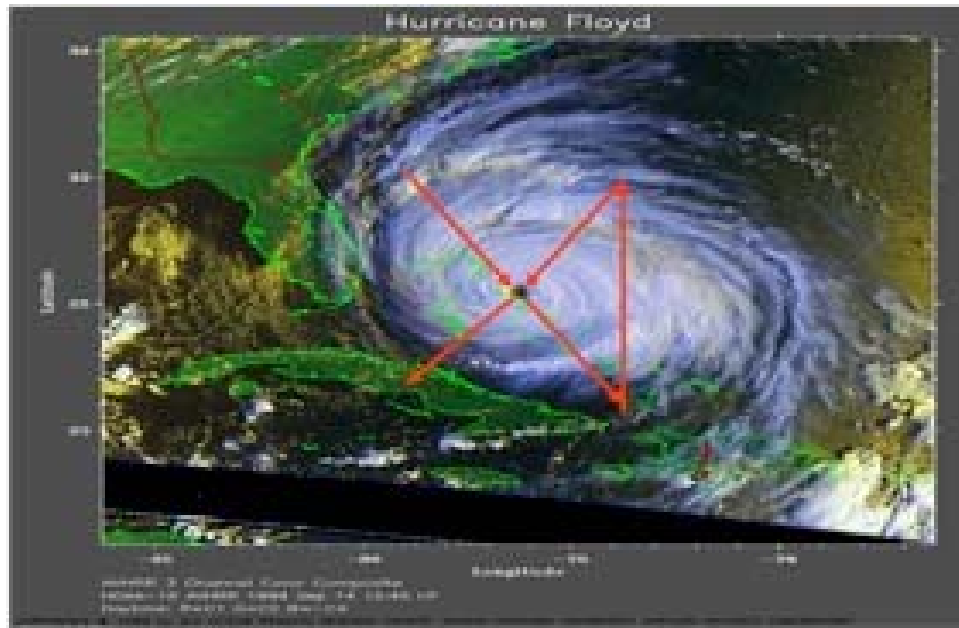


Figure 9. The alpha pattern which consists of intercardinal headings with legs 105 nautical miles in length. This alpha pattern is repeated 2 times during one mission. [<http://www.hurricanehunters.com/mission.html>]

D. HISTORY OF RECENT EXERCISES OVER THE N. PACIFIC

During August – October 2008 two special field programs [The Observing Program Research and Predictability Experiment (THORPEX) Pacific Asian Regional Campaign (T-PARC) and Tropical Cyclone Structure-2008 (TCS-08)] were conducted to obtain aircraft observations in and around tropical cyclones over the western North Pacific (Elsberry and Harr 2008). These two experiments included operation of several manned aircraft over the western North Pacific. The aircraft were directed by an operations center located at the Naval Postgraduate School (Figure 10).

The science objectives of T-PARC/TCS-08 were to obtain *in situ* observations over the lifecycle of the tropical cyclone to help increase understanding and predictability of factors that impact the evolution of the outer-wind structure of an intensifying TC over the western North Pacific. In addition to the objectives related to process studies, a

second objective was defined to measure the potential improvement to tropical cyclone track forecasts given extra aircraft observations for improved initialization of numerical models.

While four typhoons occurred during T-PARC/TCS-08, the majority of observations were obtained throughout the lifecycle of TY Sinlaku. Aircraft observations were obtained by GPS dropwindsondes (Figure 11) that measure vertical profiles of temperature, humidity, and wind. Three aircraft were flown to define the internal structure of the typhoon near Taiwan (i.e., intensity, spatial wind distribution) and the near-storm environment (Figure 12). A WC-130J from the 53rd USAF Weather Reconnaissance Squadron (Hurricane Hunters) flew inside the typhoon at an altitude of 10,000 ft to measure the intensity and spatially-varying wind structure. An ASTRA twin-engine, high-altitude business-class jet operated by the Taiwan program Dropwindsonde Observations for Typhoon Surveillance near the Taiwan Region (DOTSTAR) flew at 40,000 ft in the near-storm environment. And a FALCON jet operated out of Atsugi NAS, Japan by the Deutsches Zentrum Fur Luft- und Raumfahrt (DLR), Germany flew at 40,000 ft in a remote region that was identified as being an area where initial condition errors may grow rapidly (Harr, 2012).



Figure 10. The T-PARC/TCS-08 project area and locations of aircraft, Driftsonde, and operations centers

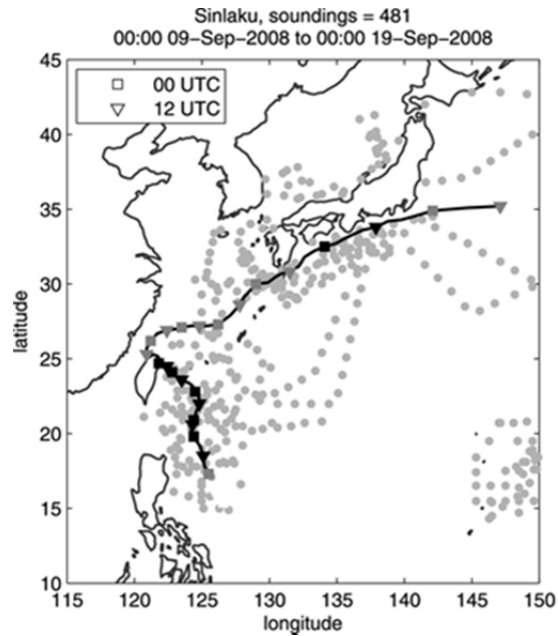


Figure 11. The distribution of dropwindsonde observations obtained during aircraft missions in TY Sinlaku during T-PARC/TCS-08 (after Weissmann et al. 2011).

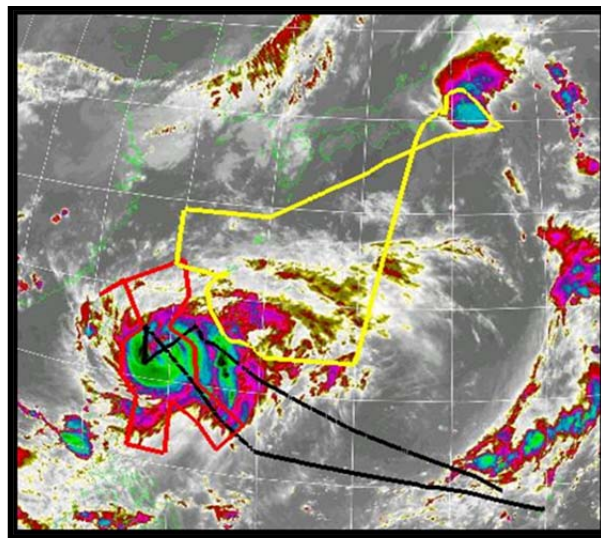


Figure 12. Enhanced infrared MTSAT imagery at 0915 UTC 11 September 2008. The WC-130J flight track is defined by the black line. The DOTSTAR flight track is defined by the red line, and the FALCON flight track is defined by the yellow line.

While all the aircraft deployed GPS Dropwindsondes, the WC130-J was equipped with a Stepped Frequency Microwave Radiometer (SFMR) to measure surface wind speeds. The DLR Falcon measured vertical profile of wind with a Doppler wind lidar, and water vapor using Differential Absorption Lidar (DIAL).

The aircraft observations in and near TY Sinlaku were used in experiments to determine whether use of the aircraft data to specify initial conditions lead to improved forecast accuracy (Figure 13). The experiments were conducted using the operational numerical global models from the European Center for Medium-Range Forecast (ECMWF), the Japan Meteorological Agency (JMA), and the U.S. National Centers for Environmental Prediction (NCEP). The degree of improvement in forecast accuracy varied with operational model. This is hypothesized to be due to different methods used to assimilate data (Weissman et al., 2010). It should be noted there were instances in which the use of aircraft data degraded operational forecasts. For example, the Japan Meteorological Agency (JMA) operational forecasts initialized at 1200 UTC 11 September were very accurate and the addition of extra observations degraded the original operational forecasts (Figure 13).

The impacts of aircraft observations were also examined with respect to the location and time of the recurvature of TY Sinlaku. Recurvature is defined as the change in track such that the storm heading changes from west of north to pass through north and eventually be east of north. Typically periods of recurvature are difficult to forecast and errors tend to increase. For TY Sinlaku, recurvature occurred 14 September. Weissmann et al. (2011) found that following recurvature the degree of improvement in forecasts that included aircraft data in the JMA and NCEP decreased. Additionally, forecasts from the ECMWF were degraded. These results are hypothesized to be due to the increase of operational upper-air data from Japan and China that were upstream of TY Sinlaku following recurvature. However, in the data-void region of the tropics, the forecasts from all models were improved, except for the period of 11 September when the JMA operational forecasts were extremely accurate. Similar results were obtained using other storm and models (Chou et al., 2011).

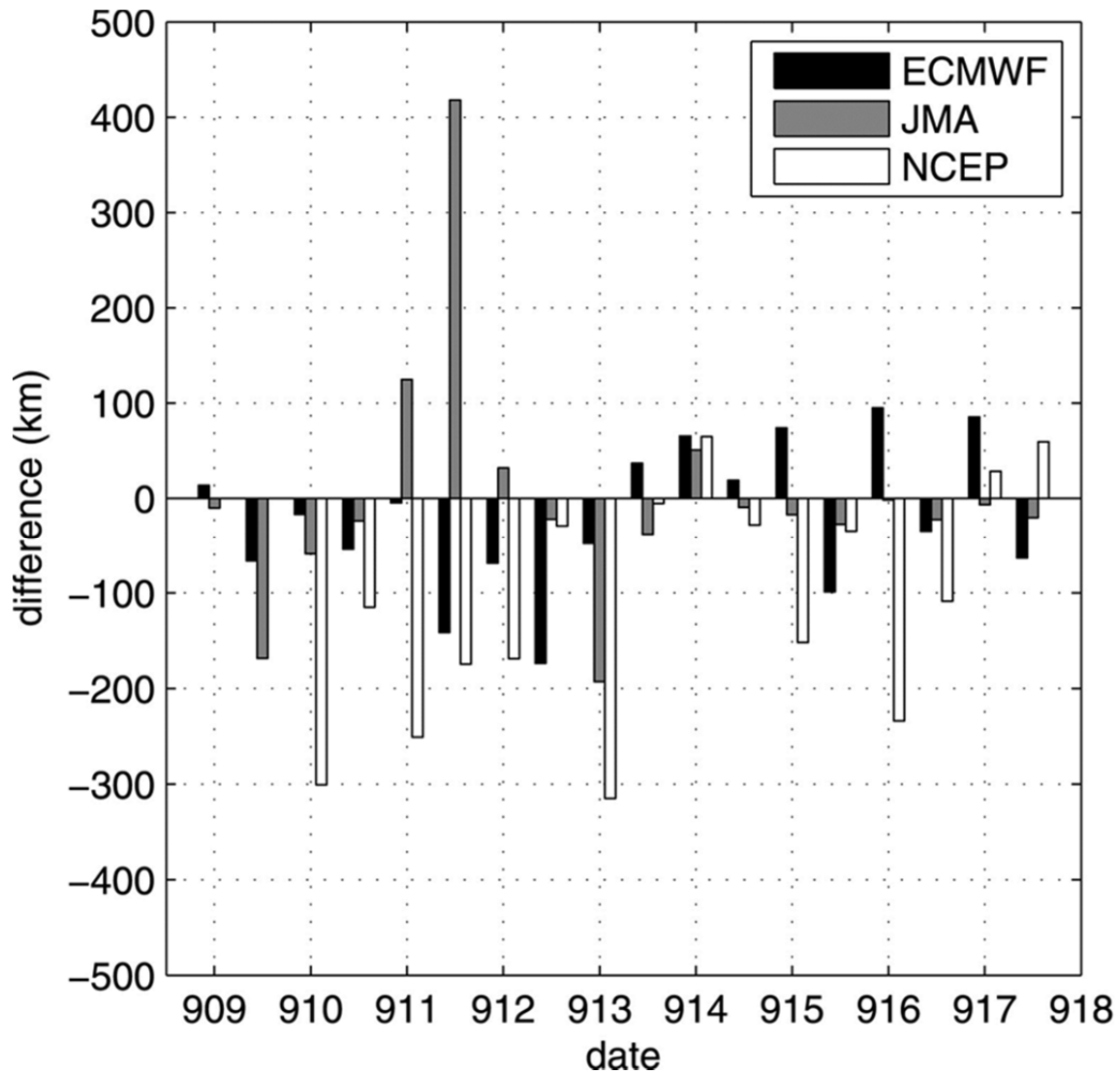


Figure 13. Forecast track error difference (km) between forecasts initiated using the T-PARC/TCS-08 aircraft dropwindsondes and operational forecasts from the listed models. Negative numbers indicate an improved forecast when the model was initialized with the aircraft data (Weissmann et al, 2010).

The study of Harnisch and Weissmann (2010) addressed the relative value of observations in the TC inner core, near environment, and remote sensitive region (Figure 14). Harnisch and Weissmann (2010) found that the observations in the immediate vicinity of the tropical cyclone (red region in Figure 14) provided the greatest improvement in track forecasts (Figure 15) from the ECMWF model. Though this is representative of only one model, this information can be beneficial in the planning of aircraft operations. Efficiency in the deployment of observations will provide a much greater impact on the improvement of forecast skill when resources are very restricted like those in the western North Pacific.

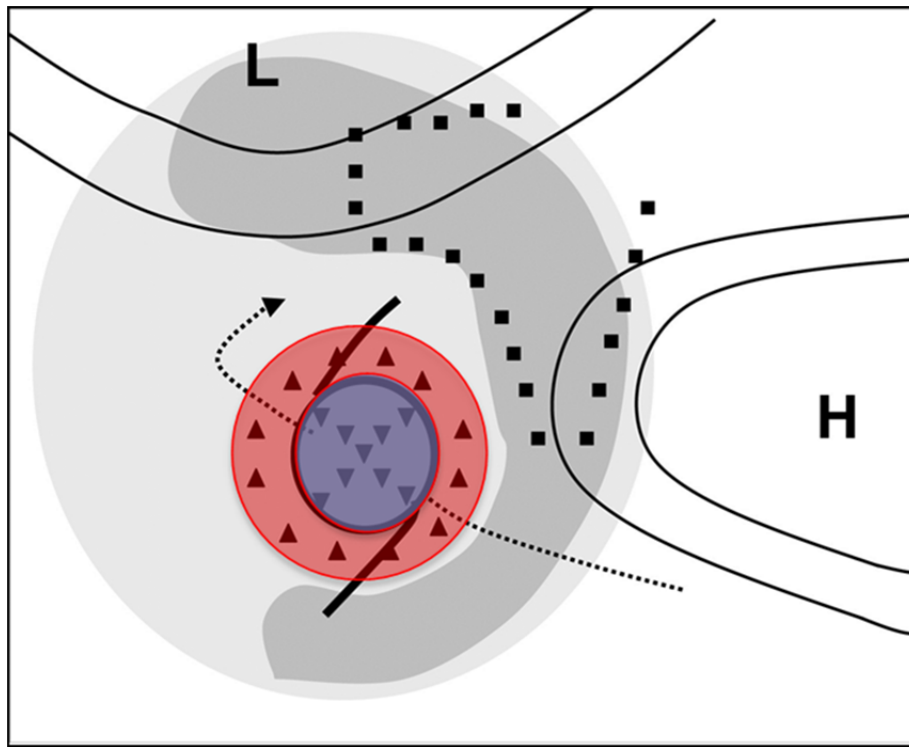


Figure 14. Schematic of aircraft observations obtained over the tropical cyclone inner core (blue), near environment (red), and remote sensitive region (dark gray). (adapted from Harnisch and Weissmann, 2010).

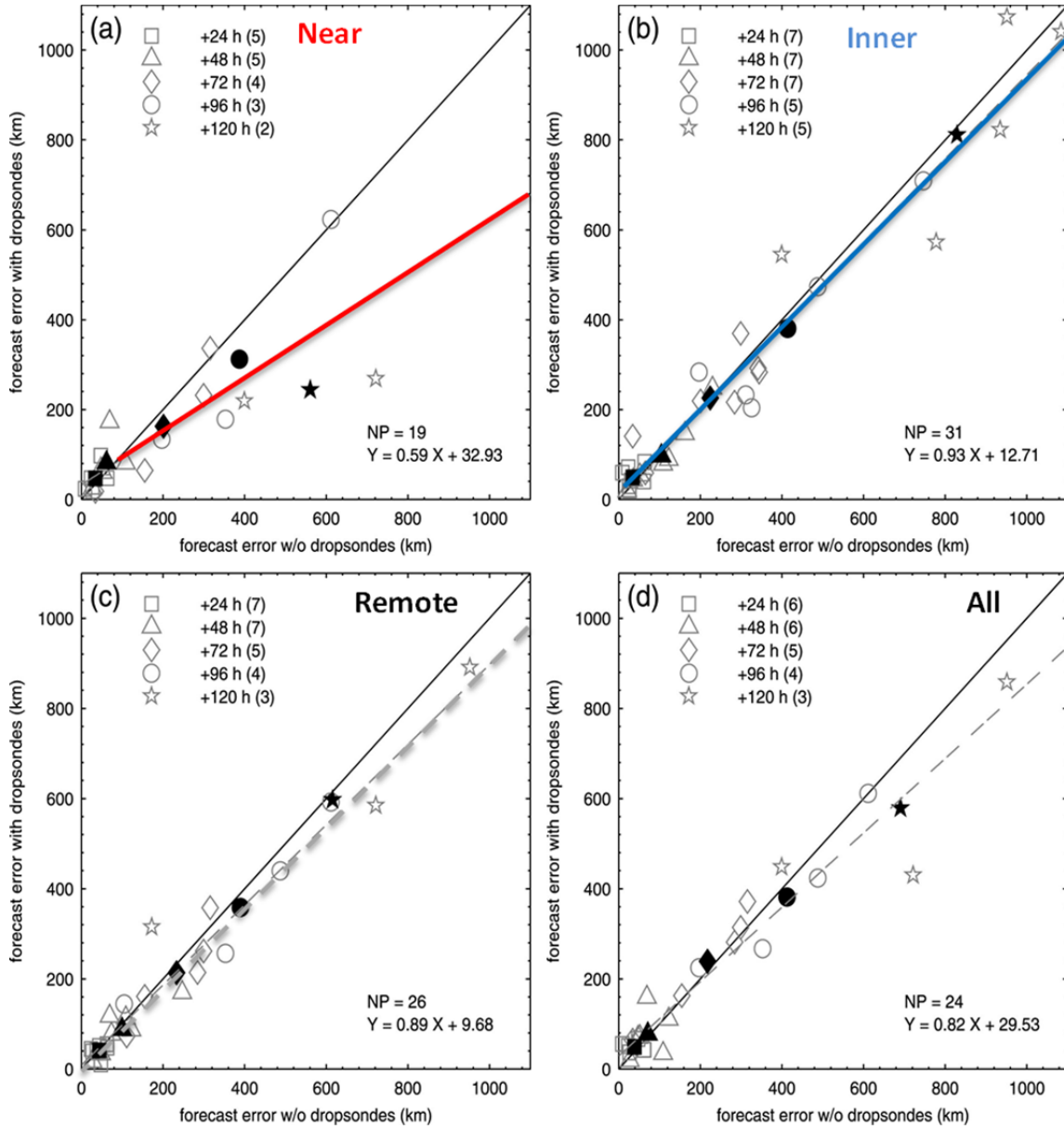


Figure 15. Comparison of forecast track errors from the ECMWF global model for TY Sinlaku when aircraft observations from the (a) near environment region, (b) inner core region, (c) remote sensitivity region, and (d) all regions are used to define the initial conditions. Colors of regression lines that define the relationship between forecasts with aircraft data and without aircraft data are defined to match the colors of each region in Figure 14 (Harnisch and

Weissmann, 2010)

Based on all data obtained during T-PARC/TCS-08, forecast accuracy for TY Sinlaku improved an average of 10–15% and a maximum of 36% (Harnisch and Weissmann 2010, Weissmann et al. 2011) when aircraft observations were included. Again, the degree of improvement varied among operational models, and this is hypothesized to be due to how data are treated in various data assimilation schemes.

Although the primary manned-aircraft platforms provide for the capability to measure many aspects of the environment in and around a tropical cyclone, they have two primary limitations. Manned aircraft duration is limited such that at most 6–8 h are available for the aircraft to be on station and collecting data. The observation time can be as little as 3 h if the ferry time to the storm is long. The primary manned-aircraft platforms defined above are also limited in terms of the maximum altitude at which they can gather observations. In a non-tropical cyclone environment, the WC-130J may operate around 30,000 ft. However, in the storm environment, the aircraft operate at 10,000 ft due to potential icing conditions at the higher altitudes. Because the typical vertical extent of a tropical cyclone is about 50,000 ft, the dropwindsonde observations deployed from the WC-130J and WP-3D only measure the lowest portion of the storm structure and the environment. This limitation reduces the utility of the observations in specifying the full three-dimensional structure of the storm in the initial conditions of a numerical model (Harr 2012). Incorporating the Global Hawk in TC reconnaissance would remove these temporal and spatial limitations, and increase the utility of the observations, providing the opportunity for enhanced initialization and improved forecasting skill.

E. HISTORY OF GLOBAL HAWK STORM ATMOSPHERIC PROGRAMS

1. NASA Global Hawk Pacific (GloPac)

In the spring of 2010, the NASA Global Hawk Pacific, or GloPac, campaign began as the first Earth Science mission conducted using the Global Hawk. Ten specialized instruments were installed on the aircraft to explore the upper troposphere and lower stratosphere. The instruments were used to study trace gases, aerosols, and atmospheric dynamics. Also, the instruments onboard the Global Hawk were used to validate sensors aboard the NASA Aura Earth-monitoring satellite. The experiment consisted of 5 flights. The first science data-collection flight in the GloPac mission was April 7, 2010. The flight path was from NASA Dryden Research Center to the Aleutians, and then back to Dryden Research Center. That 14-hour flight covered more than 4,500 nautical miles at altitudes up to 61,000 ft. The second flight that occurred a week later was a long endurance flight that extended over 24 hours to cover over 8,000 miles. The flight covered both the Pacific and parts of the Arctic. The third mission continued to go beyond testing the limits of mission duration and environmental survivability. The flight came within 400 miles of the North Pole while collecting environmental data. The objective of the final flight was to fly the Global Hawk into the coldest part of the tropical stratosphere and perform vertical profile maneuvers. While flying under the NASA Aura and CALIPSO satellites, the goal was to compare atmospheric data recorded from space satellites with data recorded by the aircraft instruments. The last flight was cut short due to an electrical problem with the instruments onboard. Overall, on the Global Hawk's first Earth-science mission, four science flights were completed, including a 28.6-hour flight to the Arctic and a 24-hour flight between the Gulf of Alaska and the tropics. Observations of cloud structures, Asian dust, and stratospheric air masses were collected, and used to validate the atmospheric data recorded by the environmental monitoring satellites.

2. Genesis and Rapid Intensification Project (GRIP)

During the summer of 2010, NASA conducted the tropical cyclone Genesis and Rapid Intensification Project (GRIP) over the tropical North Atlantic. The NASA DC-8

and the WB-57 aircraft participated with the NASA Global Hawk. The Global Hawk was configured with a suite of *in situ* and remote-sensing instruments (Table 1) used to observe and characterize the lifecycle of TCs in the Atlantic. The GRIP mission was conducted from 15 August–30 September 2010. It utilized ground networks, airborne science platform (manned and unmanned), and space-based assets (<http://airbornescience.nsstc.nasa.gov/grip/>).

Instrument Name	Measured Parameters
HIRAD: Hurricane Imaging Radiometer	Surface wind speed and rain rate over the ocean
HIWRAP: High Altitude Imaging Wind and Rain Profiler	Three-dimensional profile of winds and rain
HAMSR: High Altitude MMIC Sounding Radiometer	Vertical profiles of temperature, water vapor, and liquid water.
LIP: Lightning Instrument Package	Measures lightning, electric fields, electric field changes, air conductivity

Table 1. Instruments onboard the NASA Global Hawk during hurricane overflight missions during NASA GRIP in 2010 (Harr, 2012).

During this project, the Global Hawk was designed to use a high altitude lightweight dropwindsonde system (Figure 16). The dropwindsonde capability allowed for vertical profiles of winds, humidity, temperature and pressure for flight level to the surface. Data from the sondes were to be transmitted via Iridium or K-band satellite to a ground station. The ground station would process the data and transmit via the Global Telecommunications System (GTS) for researchers and operators to use (http://www.nasa.gov/mission_pages/hurricanes/missions/grip/instruments/index.html).



Figure 16. Global Hawk, with instruments labeled.
[\[http://www.nasa.gov/mission_pages/hurricanes/missions/grip/instruments/index.html\]](http://www.nasa.gov/mission_pages/hurricanes/missions/grip/instruments/index.html)

During GRIP, the NASA Global Hawk was used to overfly several tropical cyclones (Figures 17a,b). A total of 113 flight hours were used over four storms -- Frank, Earl, Karl, and Matthew (Zipser and Heymsfield, 2011). In each case, flight operations were conducted from the NASA Dryden Flight Research Center, California.

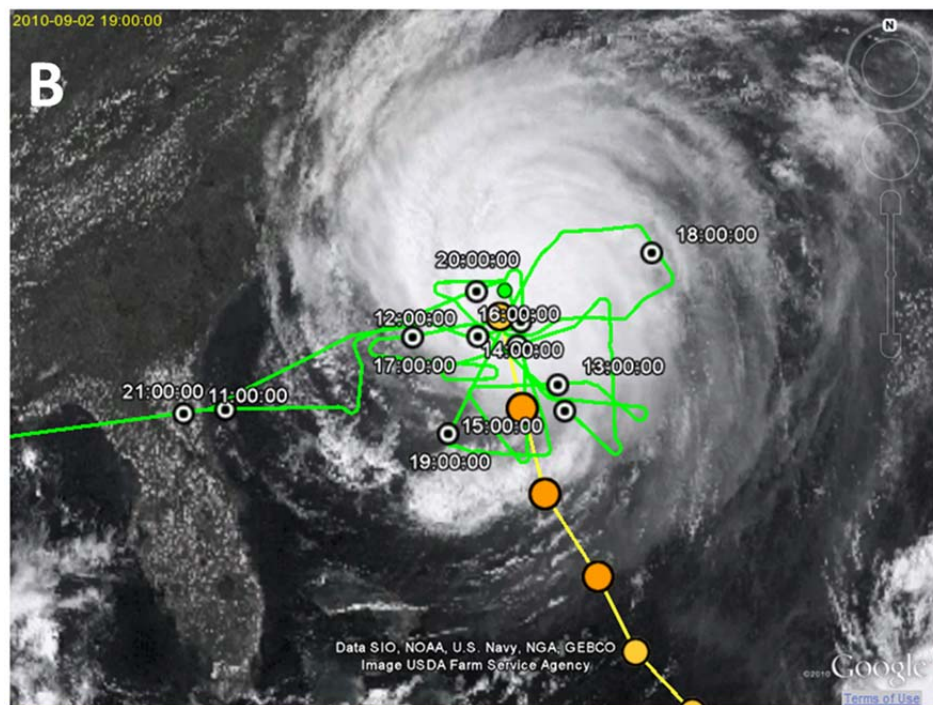
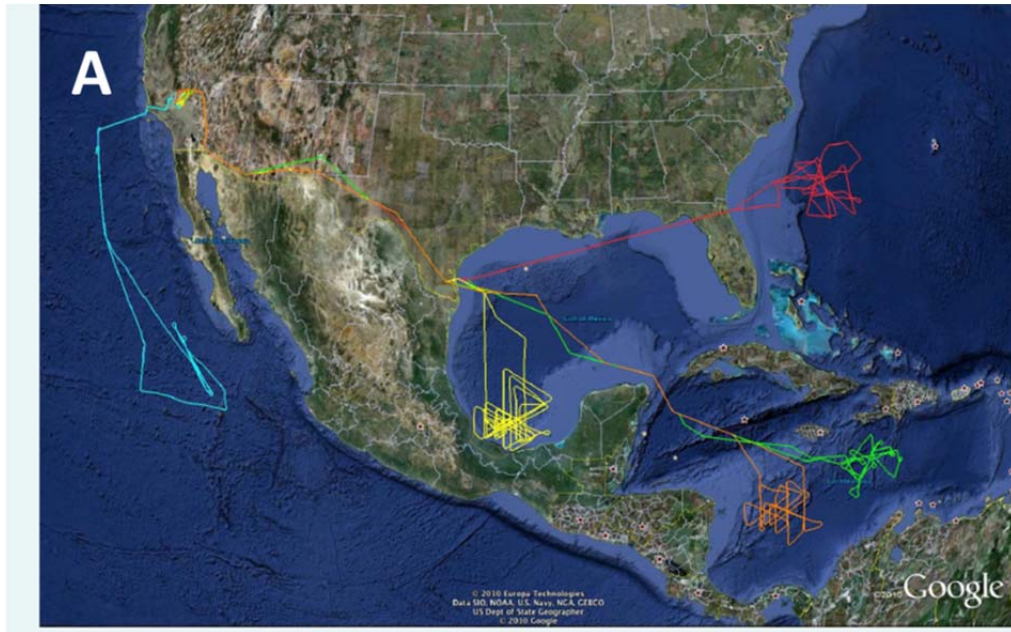


Figure 17. (a) Flight tracks of the NASA Global Hawk utilized during August-September 2010 as part of GRIP. (b) Details of the flight track (green lines) over Hurricane Earl during September 2010. The orange circles and yellow line define the track of Hurricane Earl (Images obtained from <http://grip.jpl.nasa.gov>)

The objectives of the Global Hawk missions were to define the character of the inner tropical cyclone structure and the large-scale environment in which the tropical cyclone existed. Unfortunately, the dropwindsonde was not functional and no dropwindsondes were deployed and none of the data obtained from GRIP were used to initialize operational forecast models.

3. Winter Storms and Pacific Atmospheric Rivers (WISPAR)

Atmospheric rivers are relatively narrow regions in the atmosphere that transport large amounts of water vapor across the Pacific Ocean and other regions with the potential of bringing heavy precipitation to coastal regions. During the winter of 2011, NOAA conducted long-duration flights over the Arctic and Pacific Ocean to explore atmospheric rivers and Arctic weather. They collected targeted observations using the Global Hawk, and a NOAA G-IV aircraft.

The WISPAR experiment was conducted through a collaborative effort among NOAA, NASA, and the National Center for Atmospheric Research (NCAR). The objective of the program was to demonstrate the operational and research applications of the dropwindsonde system on a Global Hawk with the goal of improving understanding of how atmospheric rivers form and behave. This understanding could lead to improved operational offshore weather predictions.

One of the instruments used aboard the Global Hawk was the High-Altitude Monolithic Microwave Integrated Circuit Sounding Radiometer (HAMSR), which is an advanced water vapor sensor. This radiometer was used to analyze heat radiation emitted by oxygen and water molecules in the atmosphere to determine their density and temperature (Wick, 2011). Thus vertical profiles of temperature, water vapor, and liquid water are provided. The HAMSR data were used to quantify how much water vapor was located between the aircraft and the surface of the ocean (Wick, 2011).

During the mission, an automated dropwindsonde system called the Airborne Vertical Atmospheric Profiling System (AVAPS) was installed on the NASA Global Hawk. Developed by NCAR, this system carried 88 dropwindsondes per flight. Each

dropwindsonde could be released remotely by a pilot located at the NASA Dryden Flight Research Center in coordination with a FAA controller.

The unmanned Global Hawk took off from Dryden February 11 and landed 20 h later (Figure 18). During this initial flight, 37 dropwindsondes were dispensed, making it the first successful use of a dropwindsonde system on this aircraft. During the three flights a total of 177 dropwindsondes were dispensed.

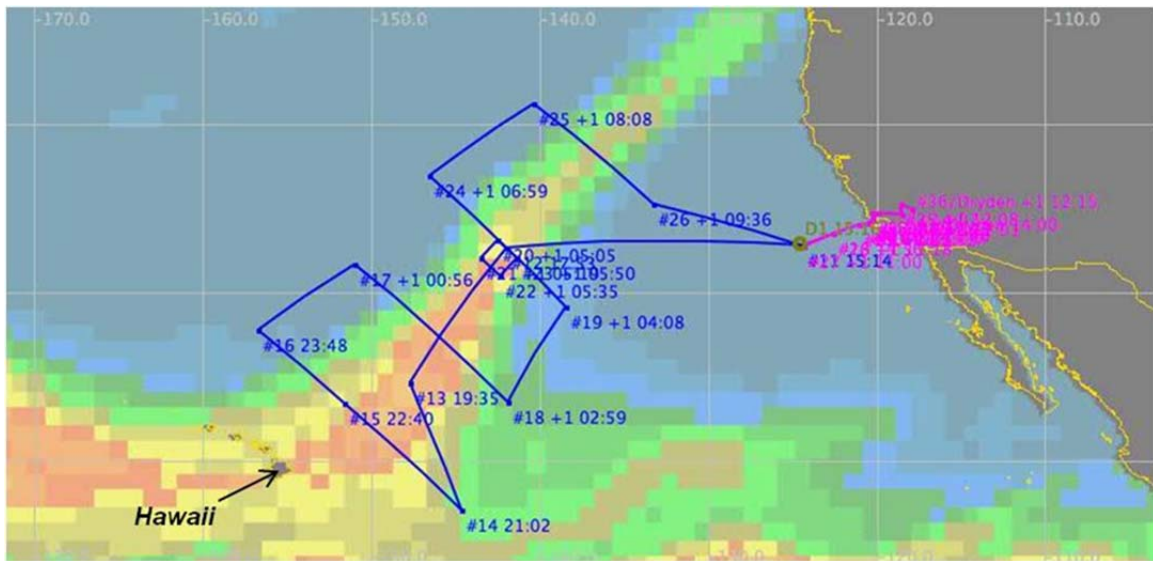


Figure 18. Flight path of the first WISPAR flight on Feb. 11th, 2011.

On 3-4 March, the Global Hawk deployed 70 sondes during a 24-hr flight period over a winter storm in the North Pacific (Figure 19). The NOAA G-IV aircraft in coordination with the Global Hawk, released dropwindsondes into an atmospheric river west of Hawaii that was associated with the developing winter storm sampled by the NASA Global Hawk and documented another case where an atmospheric river appears to have tapped tropical water vapor (Wick, 2011).

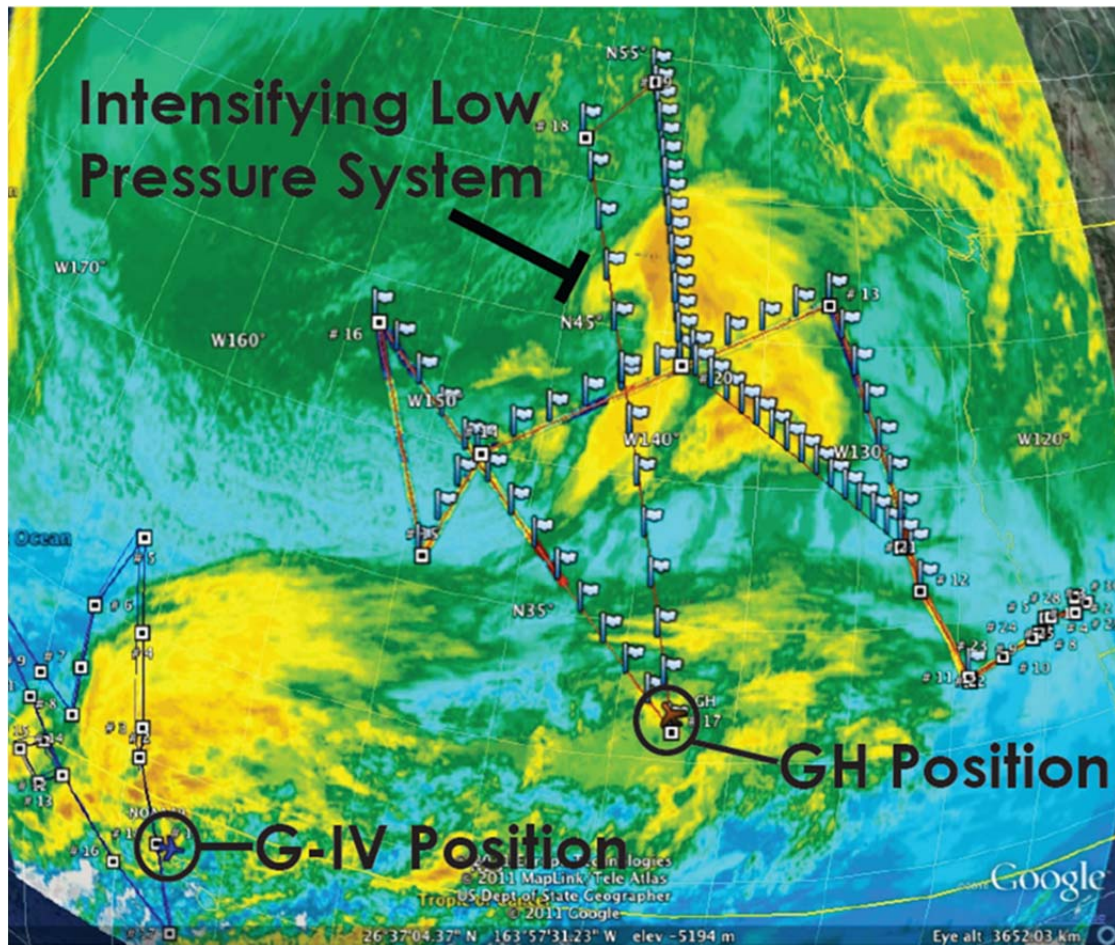


Figure 19. Coordinated flights of NASA GH and NOAA G-IV with GOES West-IR image showing winter storms targets. GH and G-IV aircraft positions are shown in real time in RTMM. GH flight track also shows the planned drop locations. [<http://www.esrl.noaa.gov/psd/outreach/resources/handouts/wispar-2011.v2.pdf>]

On 9–10 March the Global Hawk flew into the Arctic stratospheric vortex flying as far north as 85° latitude. During this 25-hour flight, the Global Hawk released thirty-five sondes in the Arctic and then went on to deploy thirty-five more in an atmospheric river and winter storm en route to and from the Arctic (Figure 20). The dropwindsonde deployments in the Arctic demonstrate the capability of the Global Hawk to conduct operations in remote regions of the earth's atmosphere and the value of observations in the Arctic atmosphere where *in situ* measurements are very limited (Wick, 2011).

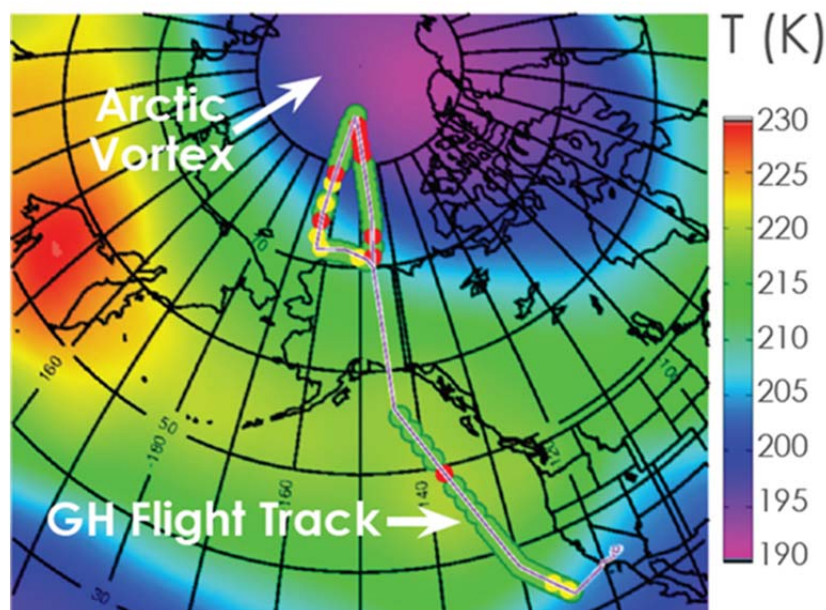


Figure 20. GH flight track with actual drop locations (colored circles) during Arctic flight showing very cold temperatures from NCAR/NCEP Version 2 reanalysis data at 70 hPa (~60,000 ft) sampled in the Arctic vortex region.

III. REQUIREMENTS

In 2009, Brigadier General William Uhle, USPACOM Deputy Director of Operations, set forth a mandate to reduce the area of uncertainty about the forecast position by 50% to increase the maneuverability of U.S. and coalition forces near a cyclone (Figure 21). General Uhle stated that increasingly accurate forecasts with less uncertainty will decrease the number of unnecessary storm evasions and provide for efficient sea and air space management, which would result in substantial savings in operating costs (Uhle, 2009).

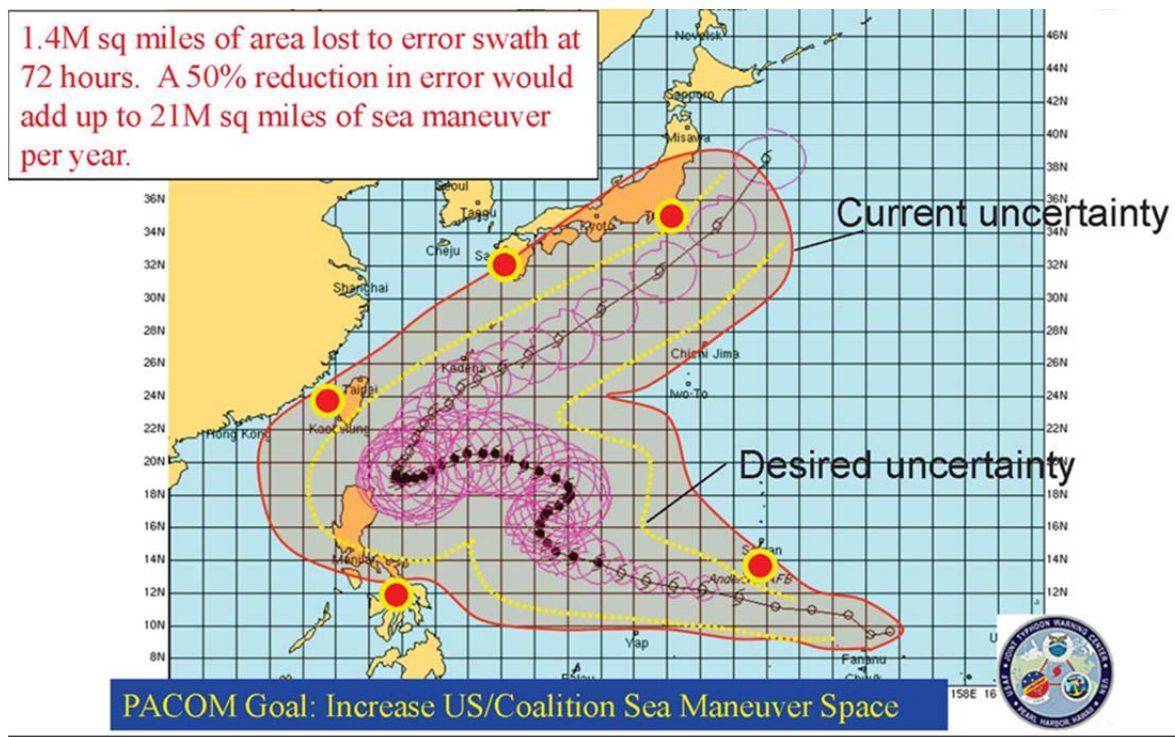


Figure 21. Schematic of current and potential forecast uncertainty in the forecast track of a tropical cyclone over the western North Pacific. Magenta circles define the analyzed radii of tropical storm force winds. (adapted from a slide kindly supplied by CAPT. M. Angove USN).

The operational forecasts of TC track and intensity serve as the basis for operational planning, which could range from a ship diverting its normal course to the evacuation of a city. Often the most critical factor in planning for TC impacts is the the degree of uncertainty in the current forecast track, structure, intensity, and rainfall distribution. Potential impacts must be assessed relative to the uncertainty.

A. OBSTACLES

Brigadier General Uhle set the requirement to reduce uncertainty such that it must be achieved by the year 2030. To accomplish this goal, the reduction of track uncertainty would have to average approximately 3% per year. However, as discussed above with reference to Figure 21, the rate of forecast improvement in the western North Pacific over the past eight years has been very small. Without a major increase in the rate of improvement in forecast skill, which is typically linked to specific advancements in understanding, it will not be possible to meet the requirement set forth by Brigadier General Uhle. As discussed above, increases in understanding are often based on new observations of key physical processes. Over the WPAC, observational capabilities are limited to remotely-sensed data from polar-orbiting and geostationary satellites. However, polar-orbiting satellite assets in this region have been reduced, through attrition and a gap with the development and launch of new satellite platforms (Figure 3). In addition to limited satellite capability, no operational aircraft reconnaissance occurs in this region. Therefore, no *in situ* measurements are available to improve forecast model initialization. If no additional efforts are made to gain *in situ* observations in and near TCs, observational capability and potential increases in understanding will continue to be negatively impacted, and this operational requirement set forth by Brigadier General Uhle will not be met.

B. OPPORTUNITIES

The recent T-PARC/TCS-08 programs over the Western North Pacific proved that for specific cases, *in situ* measurements positively impacted forecast skill. However, the flights in which *in situ* measurements were obtained were limited by the elevation at which they could record environmental data, and the length of time on station to conduct

operations. Use of the Global Hawk to collect *in situ* measurements would provide vertical profiles of winds, humidity, temperature and pressure for the entire structure of the tropical cyclone since the Global Hawk can fly at an altitude of 65,000 ft (19.8 km) and be completely above the storm. With the ability to deploy dropwindsondes at such great heights, scientists could explore the dynamical processes at low, mid, and upper levels. Also, the representation of TC structure in initial conditions of numerical models could be improved.

Consistent *in situ* measurements have never been collected in the TC outflow layer. The only measurements providing data on the outflow are from geostationary and polar-orbiting satellites. Changes to the outflow layer of tropical cyclones have been hypothesized to lead to large changes in structure and intensity. Observations of outflow could examine whether these TC intensity changes and outflow changes are due to the internal processes of the TC convection, the surrounding environmental interactions, or both.

The upper-level TC outflow region is a critical aspect of TC structure and though its influence on intensification is being studied, it is still poorly understood. One hypothesis is the outflow responds to changes in the secondary circulation. This circulation could be one caused by lower boundary conditions and forcing of deep convection in the inner-core. The reasoning behind this is due to enhanced radial inflow, which allows for more heat, moisture and high angular momentum air to be advected inward, resulting in increased deep convection in the inner-core. This would lead to intensification provided the outflow is capable of providing ventilation to the environment (Figure 22).

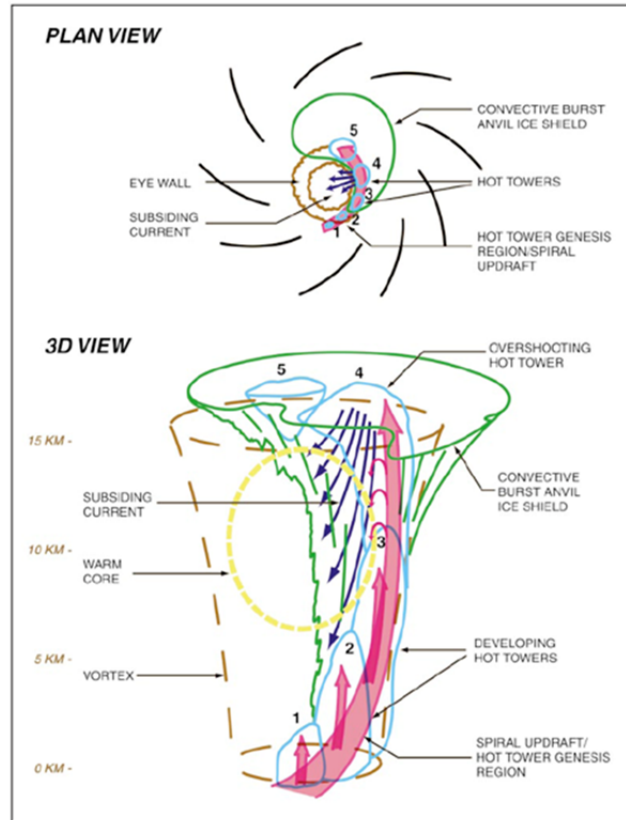


Figure 22. Schematic of the role of deep convective bursts in hurricane intensification. The concept portrayed in this figure is that the deep towers contribute to subsidence in the eye of the developing storm.
[\[http://espo.nasa.gov/missions/hs3/content/HS3_Hurricane_Intensity_Change_and_Internal_Processes\]](http://espo.nasa.gov/missions/hs3/content/HS3_Hurricane_Intensity_Change_and_Internal_Processes)

It has also been noted that outflow (Figure 23) from intensifying TCs often link to the synoptic-scale, upper-level environmental flow, while non-intensifying TCs have no such link (Figure 24). On the other hand, it could be hypothesized that interactions between the synoptic-scale environment and the TC outflow invoke changes to the secondary circulation, and that will lead to an increase in convection and the lowering of surface pressure, and thus intensification. The primary hypotheses supporting this theory are as follows:

- Intensification is favored in regions of low upper-level inertial stability (combination of the Earth vorticity and TC outflow vorticity).
- Eddy flux convergence of absolute angular momentum at upper levels from mid-latitude troughs can further affect the upper-level structure and intensity changes in these low inertial stability regions (Figure 24)
- The induced secondary circulation from the upper-level outflow depends on the outflow structural features such as the number of outflow channels, their orientation, time evolution and depth.

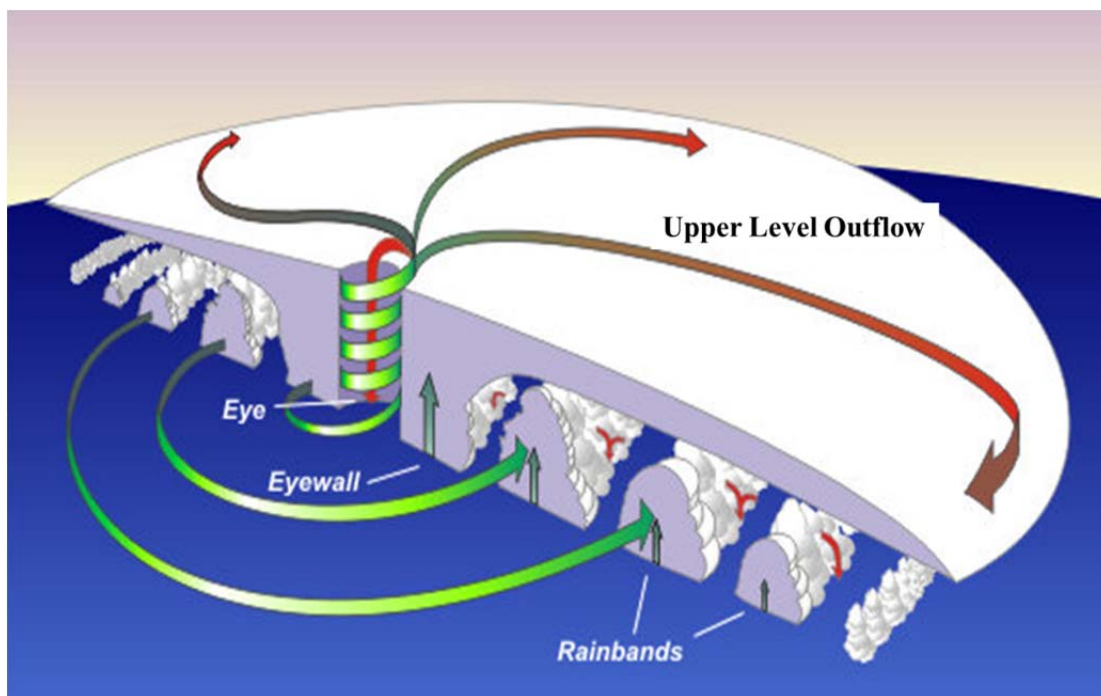


Figure 23. Schematic of the inner and outer bands of a tropical cyclone including outflow layer.

However, addressing these observational requirements would require a very frequent, high-resolution mapping of the inner-core wind, precipitation fields, and the formation of the warm core in the developing eye (Justice, 2012). With the Global Hawk's long flight

duration (~20 h), the evolutionary cycles of the TC interactions could be captured on time scales of hours to nearly one day within a single flight.

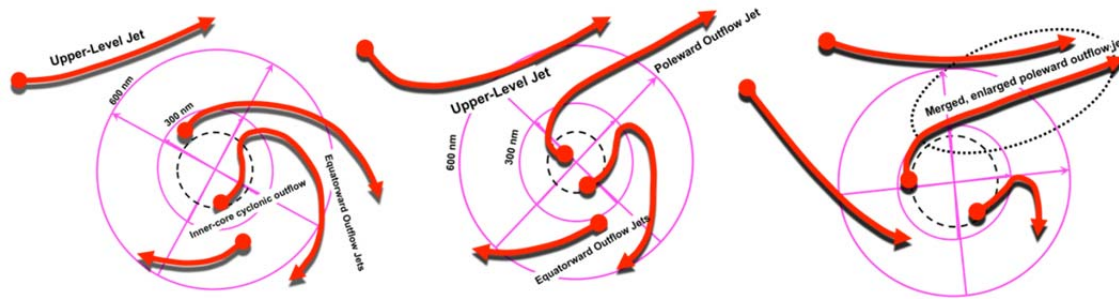


Figure 24. Diagram of the interaction between the outflow layer and its environment at the upper levels. The thick arrow defines primary upper-level flow due to either the TC outflow or midlatitude jet stream.

C. DATA COLLECTION PROCEDURES

Current operational reconnaissance missions involve many types of aircraft and methods for collecting data. Manned aircraft are limited in temporal and spatial coverage, which may not provide new observations required to improve understanding and forecast accuracy. Many innovations have emerged and are still emerging to advance observational capability and understanding of TCs. In this section, several unmanned systems are discussed with respect to the potential use as observatory platforms in the environment of a TC.

1. The Altair Integrated System Demo Flight

In April – November 2005, NOAA and NASA conducted the Altair Integrated System Flight Demonstration Project in cooperation with General Atomics Aeronautical Systems, Inc. (GA-ASI). Altair is a high-altitude, long-endurance (HALE) UAV platform built and operated by GA-ASI (Figure 25).



Figure 25. The Altair High Altitude Long Endurance (HALE) UAV

The science objectives of the demonstration project were to measure ocean color, atmospheric composition, and atmospheric temperature. Specific flight objectives included sampling low-level jets in the eastern Pacific Ocean that bring moisture to the southwestern North America (e.g., atmospheric rivers); sampling regions of high potential vorticity at mid-latitudes that result from transport of polar air equatorward, and imaging of the Channel Islands National Marine Sanctuary (CINMS) to examine shorelines and evaluate the potential for marine enforcement surveillance.

The HALE UAV used *in situ* measurements of gases such as ozone, halocarbons and nitrous oxide. Ocean color was measured with a multi-channel optical radiance sensor. Remote sensing of ocean color provides high resolution chlorophyll-a concentration data.

Remote-sensing instruments, such as a passive microwave sensor was used to measure the vertical distribution of water vapor. The Altair UAV also demonstrated a Digital Camera System (DCS) and an Electro-Optical Infrared (EO/IR) Sensor. The DCS was used in shoreline mapping and in along-shore/inland feature characterization for habitat mapping/ecosystem monitoring. The EO/IR system was used for day/night fisheries surveillance and enforcement, along with marine mammal surveys.

This experiment conducted flights at 45,000 ft (13.7km) with durations up to 18 hours. Five flights were completed, for a total of 45.3 flight hours plus 20.6 on integration flights.

It is clear from the description above that many of the observing capabilities demonstrated in the HALE UAV project are applicable to measure the environment of a TC. However, with an altitude capability of 45,000 ft, it is not possible for this particular aircraft to fly over the top of a mature TC.

2. Aerosonde UAS



Figure 26. The Aerosonde UAS

On 16 September 2005, NOAA, NASA successfully directed an Aerosonde into tropical storm Ophelia. This was the first time an autonomous vehicle was flown into the core of a mature TC.

The Aerosonde flew at 500 feet above the ocean surface and provided near-surface wind speed measurements, as well as high-resolution thermodynamic and kinematic observations within the low-level inner core. Observations at the TC-ocean interface provide measurements of the processes that provide the transfer of energy from the ocean to the atmosphere.

The Aerosonde is a small single-engine aircraft that may be launched from a moving vehicle. The Aerosonde carries a set of instruments that provide flight-level measurements of atmospheric state variables. Communication requires a portable computer with a line-of-sight capability up to 120 nmi.

Although the Aerosonde operation has been successfully completed in several TCs, the capability is limited to near shore locations and to low levels in the atmosphere.

3. Fire Missions

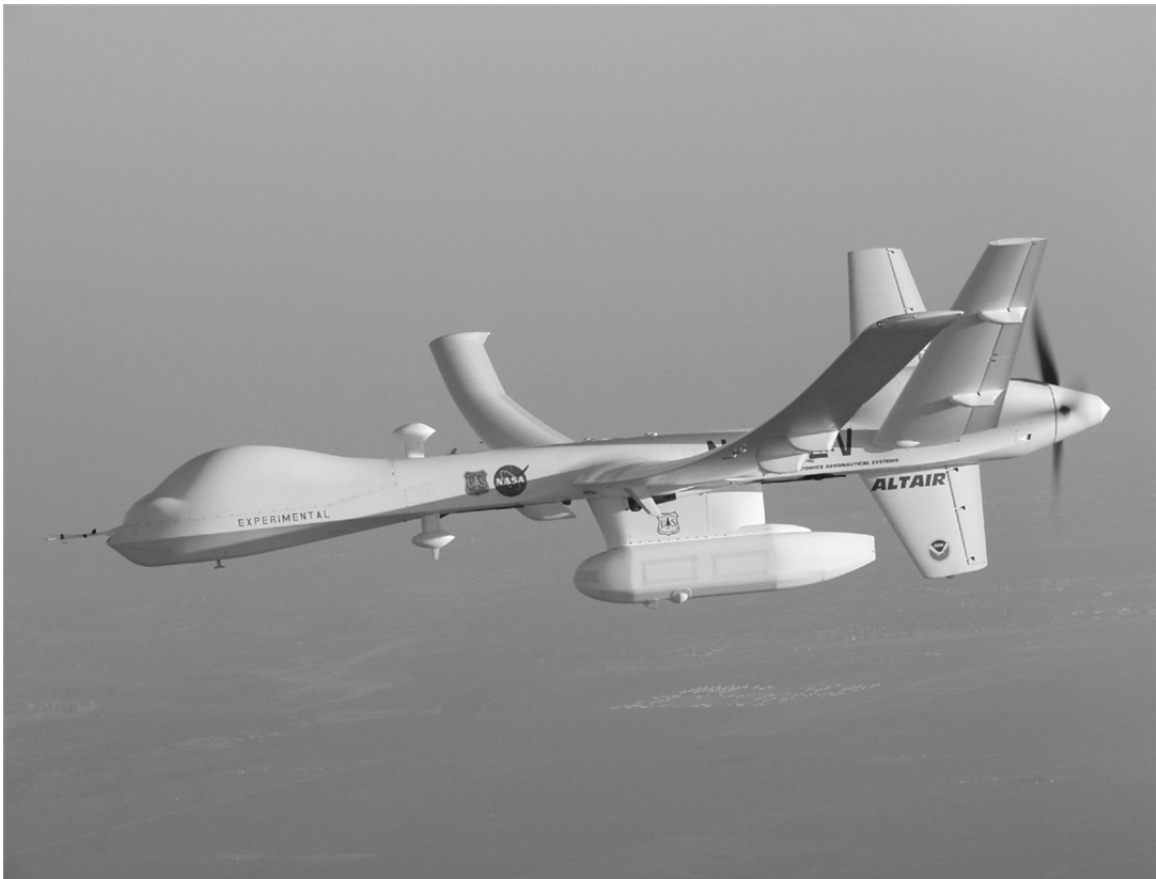


Figure 27. The Altair UAS with an infrared imaging sensor in its underbelly pod.
[www.dfrc.nasa.gov/gallery/photo/index.html]

The Altair Western States Fire Mission teamed with NASA Dryden Flight Research Center (DFRC), NASA Ames Research Center (ARC) and General Atomics Aeronautical Systems Inc. (GA-ASI) (San Diego, California) teamed with the USDA Forest Service to demonstrate the capability of an Unmanned Air Vehicle (UAV) as a wildfire remote sensing platform. The experiment demonstrated the combined use of a NASA ARC-designed thermal multispectral scanner integrated on a large payload capacity UAV, a satellite image data telemetry system and near-real-time image georectification. In the Ground Control Station (GCS) , images were collected from the multispectral scanner and retransmitted to the Collaborative Decision Environment (CDE) at ARC via the Internet. The images were processed with georectification software to overlay them precisely on a global map as depicted in Figure 28. The images could then be viewed from any location.

The primary objective was to achieve science flight(s) of 20–24 h over an active fire with the fire sensors operating. Though the Altair flight mission completed many long endurance flights, its altitude of 43,000 ft would not provide a complete depiction of a mature TC in the vertical and horizontal.

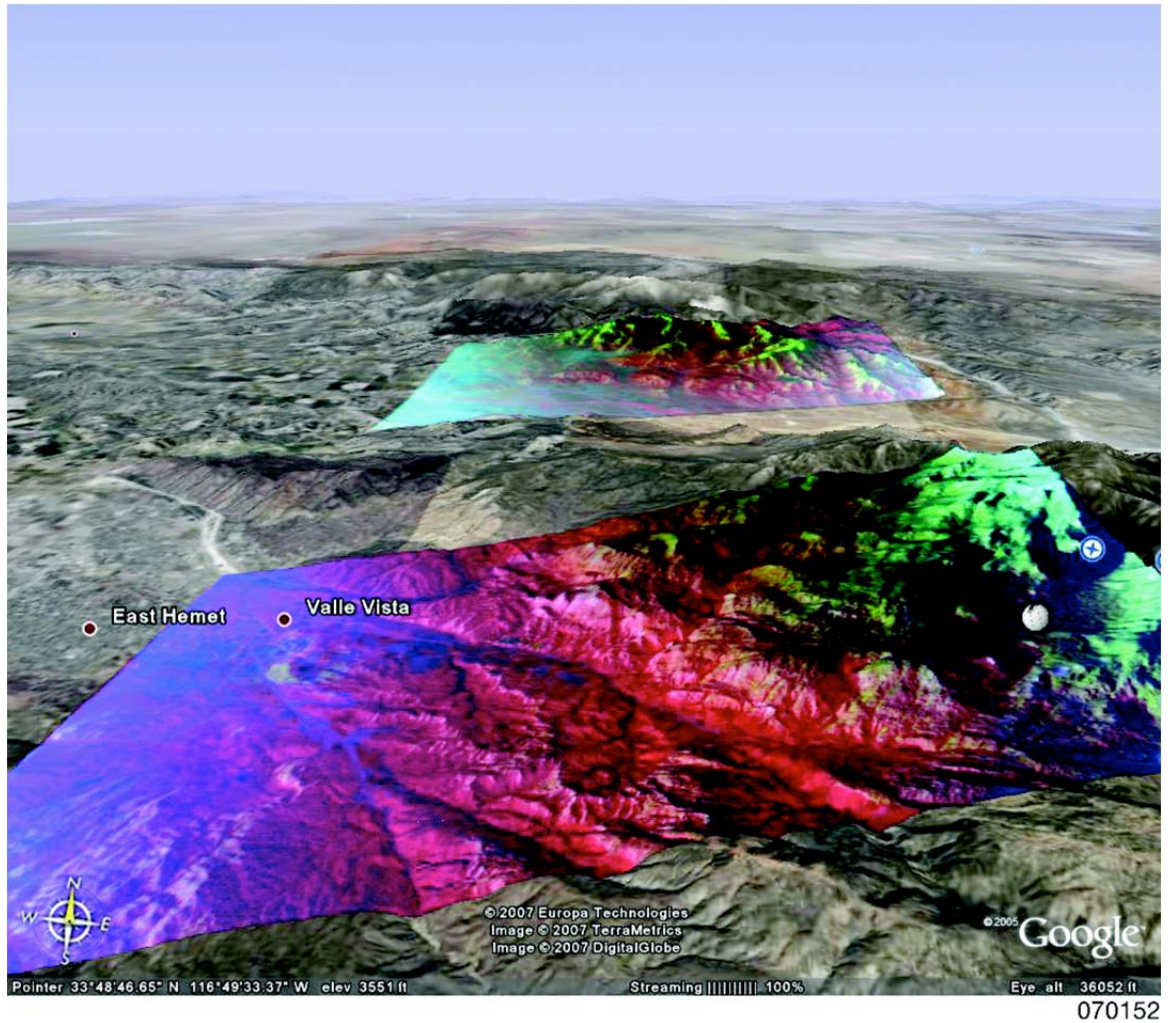


Figure 28. Mult-spectral scanner images from the Esperanza Fire, October 28, 2006. Overlaid on GoogleTM Earth Map.

4. Maldives Autonomous Unmanned Aerial Vehicle (AUAV) Campaign



Figure 29. Photo of the lightweight UAV's used in the Maldives AUAV Campaign.

In March of 2006, scientists from the Center for Atmospheric Sciences and the Center for Clouds, Chemistry and Climate and Scripps Institution of Oceanography, University of California at San Diego conducted an experiment to collect data on pollution and dust from surrounding deserts of Saudi Arabia, Southwest Asia, and Southern Asia. The objective was to measure and assess the impacts of the dust on global dimming at the sea surface, energy absorption in the atmosphere, and cloud properties. Black carbon was also measured to determine its role in solar heating of the atmosphere. Three lightweight UAVs (Figure 29) were used to record observations below, above and within the cloud layer. Through real-time data and in-cloud video, the observations were able to be tracked.

Like many of the UAV's mentioned above, the AUAV used during this campaign was also limited in the maximum altitude at which it could fly. Additionally, the payload required to depict the entire three-dimensional structure of a mature TC would be too large for this aircraft.

5. Weather In-Situ Deployment Optimization Method (WISDOM)

The Weather In-Situ Deployment Optimization Method (WISDOM) is a system of recording environmental data with small super-pressure balloons that float at constant levels in data-void regions of the atmosphere. The balloons are equipped with GPS positioning and satellite communications capability, and their data are transmitted in real time via satellite ground station to the MADIS servers at NOAA/ESRL.

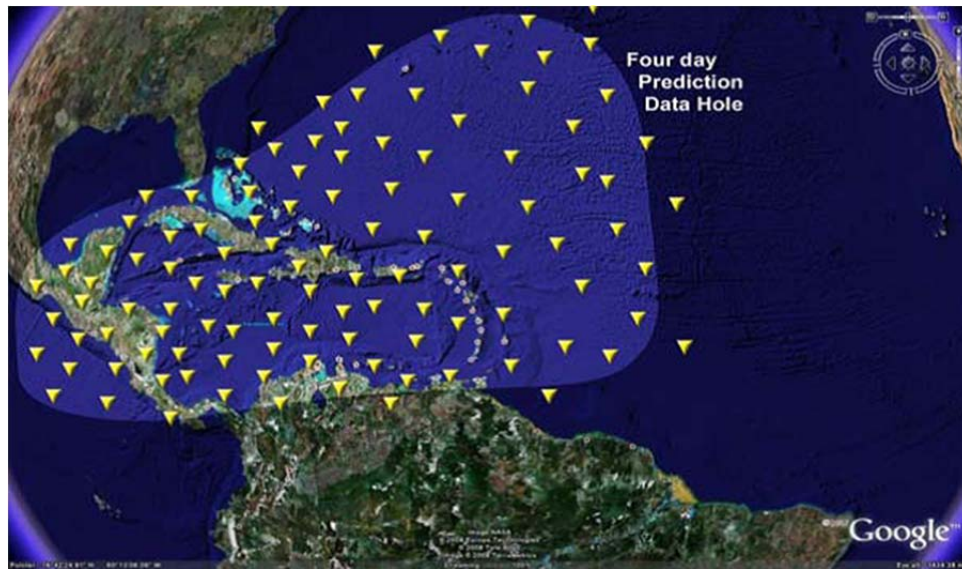


Figure 30. Possible locations of WISDOM balloon deployments.



Figure 31. WISDOM balloons are prepared for launch.

Though the experiment covers a large area, it only provides data of the surrounding environment. Additionally, once released the WISDOM balloons cannot be flown into the center of a mature TC, an area where data will be needed to increase understanding of the physical processes involved.

6. GALE UAS

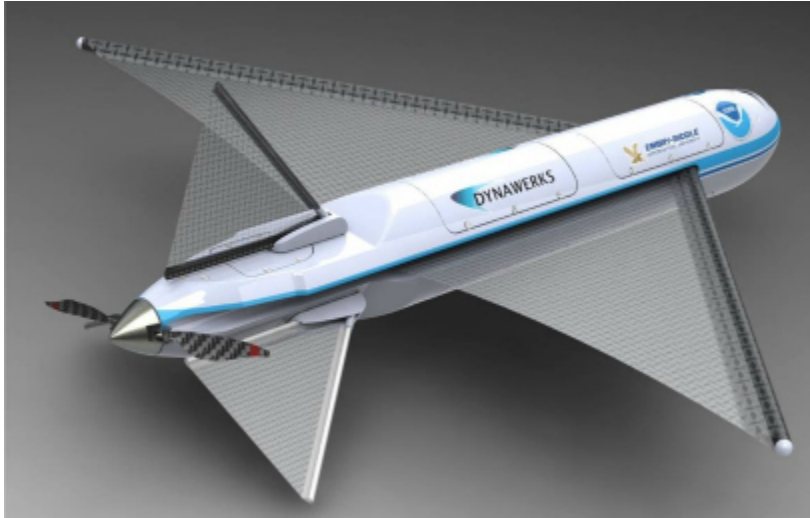


Figure 32. The GALE UAS

The GALE UAS is another instrument used to record and transmit data at low altitudes. It is a small electric-powered unmanned aircraft with 1–2 hour endurance and is capable of carrying a 1–2lb payload. GALE has been used to study fully developed TCs with well-defined eyes. To achieve its mission, it is deployed from a P-3 Orion aircraft at 10000 ft. When initially dropped, it descends without electrical power, and then activates its motor at the 5000 ft level where it is controlled from the P-3 aircraft (Figure 33).

With a maximum endurance of 2 hours, and limited altitude, data on the formation and structure of a TC will not add to increased understanding of the mid and upper levels. Additionally, since the P-3 will have to operate within the eye, daylight missions will be required so as to maintain P-3 visual contact with the eyewall at all times (Cione, 2012)

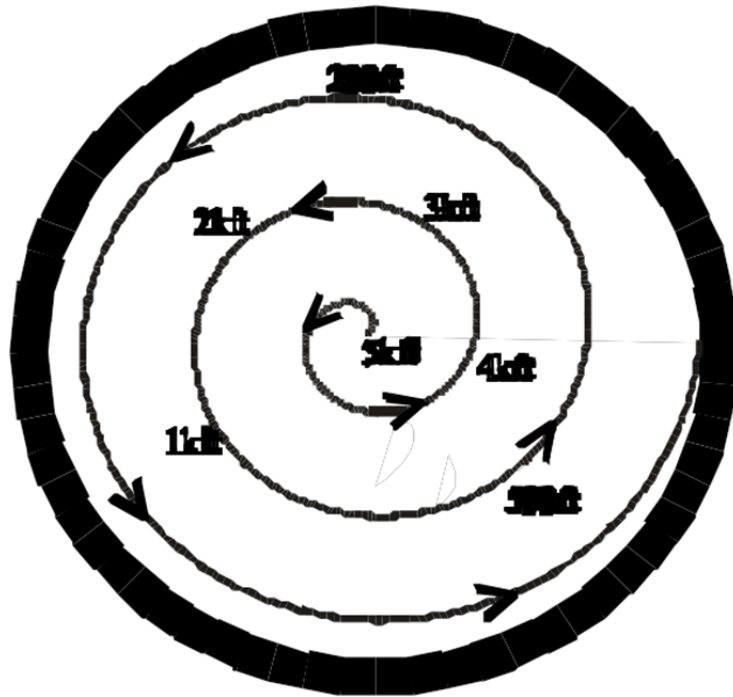


Figure 33. Schematic that depicts release of the GALE UAS from a P-3 just inside a TC eyewall. The thin line with arrows defines the glide path of the GALE UAS to the surface. (Cione, 2012)

7. Hurricane Severe Storm Sentinel (HS3)



Figure 34. The NASA Global Hawk at the Dryden Flight Research Center

The Hurricane and Severe Storm Sentinel (HS3) is a five-year mission specifically targeted to investigate the processes that underlie hurricane formation and intensity change in the Atlantic Ocean basin. The HS3 program will utilize two Global Hawks, one with an instrument suite geared toward measurement of the environment and the other with instruments suited to inner-core structure and processes. The environmental payload includes the scanning High-resolution Interferometer Sounder (HIS), dropwindsondes, the TWiLiTE Doppler wind lidar, and the Cloud Physics Lidar (CPL) while the over-storm payload includes the HIWRAP conically scanning Doppler radar, the HIRAD multi-frequency interferometric radiometer, and the HAMSR

microwave sounder (Table 2). Field measurements will take place for one month each during the hurricane seasons of 2012–2014.

Instrument	Raw Data (MB/hour)	Data Rates (kbps)	Downlink Data Parameter	Data Products
CPL	~500	1.726 per profile, one profile every 0.1 s	Single wavelength profiles of attenuated backscatter	Profiles of calibrated attenuated backscatter (3 wavelengths); cloud/aerosol layer boundaries; cloud/aerosol optical depth, extinction, and depolarization; color ratio
Dropsondes	1.5 (@ 5 drops/hr)	0.1	P, T, RH, and winds	Quality controlled vertical profiles of P, T, RH and GPS-derived u- and v- winds,
HAMSR	34	75	Raw power	Calibrated, geo-located brightness temperature, vertical profiles of temperature, water vapor and liquid water; precipitation structure
HIRAD	7,200	2000	Brightness temperatures	Surface wind speed, rain rate, and temperature; brightness temperature fields at 4 C-band frequencies
HIWRAP	Raw (infrequent) 576,000; processed 17,000	20	Raw power, Doppler velocity	Calibrated reflectivity, platform-corrected Doppler velocity, Surf. return, 3-D reflectivity fields and horizontal winds, ocean surface winds.
S-HIS	320	9.6	Interferogram ZPD Magnitude (Broadband Calibrated Radiance)	Infrared Brightness Temperature Spectra, IR Cloud Top Temperature, Cloud Top Height, Cloud OD, Cloud EffR, Water Skin Temperature
		38	Reduced Resolution Unfiltered Interferograms	Atmospheric Temperature and Water Vapor Profiles in Clear Sky Conditions Collocated CPL/S-HIS Observations
TWILITE	40	5	Profiles of backscattered signal radial velocity	Profiles of backscatter intensity, backscatter ratio, Doppler velocity, horizontal winds

Table 2. Instruments used on the NASA Global Hawks during NASA HS3 in 2012 .

Operated by NASA's Dryden Flight Research Center the Global Hawk is an unmanned aircraft for high-altitude, long-duration Earth science missions. With a range of 11,000 nmi, an endurance of 32h, and the capability of flying at altitudes of 65000 ft measurements may be obtained through the entire depth of the troposphere. Like many UAVs mentioned previously, the Global Hawk has satellite communication links that provide researchers with direct access to their onboard instrument packages during missions. Researchers have the ability to monitor instrument function from the ground control station and evaluate selected data in real time. The ability of the Global Hawk to autonomously fly long distances, remain aloft for extended periods of time and carry large payloads brings a new capability to the science community for measuring, monitoring and observing remote locations of Earth not feasible or practical with piloted aircraft, most other robotic or remotely operated aircraft, or space satellites.

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IV. FRAMEWORK OF AN OPERATIONAL TEST PLAN

Besides the WC-130J aircraft, the primary platforms used routinely in and around western North Atlantic tropical cyclones are the WP-3D and Gulfstream-IV aircraft. Although the primary manned-aircraft platforms provide for the capability to measure many aspects of the environment in and around a tropical cyclone, they have two primary limitations. Manned aircraft duration is limited such that at most 6–8 h are available for the aircraft to be on station and collect data. In some cases, it could be as small as 3 hours depending on the transit time. The primary manned aircraft platforms defined above are also limited in the maximum altitude at which they can gather observations. In a non-tropical cyclone environment, the WC-130J may operate around 30,000 ft. However, in the storm environment, the aircraft operate at 10,000 ft due to severe icing conditions at the higher altitudes. Because the typical vertical extent of a tropical cyclone is about 50,000 ft, the dropwindsonde observations deployed from the WC-130J and WP-3D only measure the lower portion of the storm's structure and environment. While dropwindsondes observations from the G-IV are obtained from a flight level of approximately 40,000 ft, these observations are in remote regions away from the tropical cyclone. Neither set of observations collected by the manned aircraft provide insight into the interactions of the storm and its environment at the upper levels. As a result of these limitations, the utility of the observations is reduced, along with the ability to specify the full three-dimensional structure of the storm in the initial conditions of a numerical model.

To address the objectives of improving track and intensity forecast skill, as well as reducing forecast uncertainty of tropical cyclones over the western North Pacific, the use of a Global Hawk to provide *in situ* measurements for improved initial conditions of model integrations is proposed. The use of a Global Hawk would remove both limitations related to use of the manned aircraft and increase the utility of the observations for defining the storm wind radii and structure for real time operational warnings, and as model initial conditions.

A. OPERATIONAL TEST PLAN

A test program to assess the feasibility of obtaining Global Hawk observations and the value of these observations in the environment of a tropical cyclone over the WPAC should be developed. This should begin with a set of observation system simulation experiments (OSSEs) to identify possible improvement in forecasts made without aircraft observations, by the incorporation of aircraft observations. The data obtained by the NASA HS3 program should be assessed to identify aircraft operation constraints, instrument capabilities, and value to improved forecasts. The use of the two NASA Global Hawks over the Atlantic as part of the three-year NASA HS3 program will provide experience in the use of the aircraft in and around tropical cyclones and coordination with airways regulations. The scientific goals of HS3 do not specifically address use of data for improved model initial conditions. However, the data obtained from the Global Hawk operations will provide cases for analyses designed to assess potential forecast improvements. These experiments should be conducted with respect to the T-PARC/TCS-08 results to assess the improvement that could be obtained over manned aircraft. A minimum capability is the deployment of dropwindsondes observations that may be assimilated into numerical model analyses.

In addition to aircraft observations, experiments have indicated that improved forecasts may be realized when high-resolution radar-based observations are used to improve initial conditions. Therefore, the full suite of remote sensing instruments contained on the NASA HS3 Global Hawks (Table 2) may also be valuable for improving model initial conditions. However, much research is needed to understand and define the error characteristics required to properly utilize these observations in a data assimilation system. Therefore, the minimum requirement for use of Global Hawk observations over the western North Pacific is for a dropwindsonde system such as the AVAPS that currently exist on the environmental NASA Global Hawk.

The culmination of this operational test plan would be the use of a Global Hawk aircraft in the western North Pacific to obtain observations in and around tropical cyclones that would lead to a WPAC airborne dropwindsonde observational data base. This database could be utilized to improve TC intensity change prediction using the new

generation of coupled models such as the Tropical Cyclone Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS-TC).

The earliest season for this test would be the summer of 2015. To conduct the operational test, the minimum requirement is for a Global Hawk with dropwindsondes capability. This could be achieved with a NASA Global Hawk or the implementation of a dropwindsondes system on a USAF or USN Global Hawk.

Finally, the operational test over the WPAC should have a research component via partnership with sponsor agencies such as the Office of Naval Research and the National Science Foundation. The research component should have objectives related to observing strategies for improved model initial conditions plus improved understanding of tropical cyclone structure and intensity changes.

B. COORDINATION

The primary goal is to define the scenario by which a Global Hawk could be used to support the JTWCC and DoD assets throughout the western North Pacific by providing tropical cyclone reconnaissance observations of surface wind radii and vertical structure on an as-needed basis. Operation of the Global Hawk would require an interface among several USAF and USN commands. Additionally, liaison with NASA and other civilian agencies would be beneficial for the establishment of operational guidelines and specification of instrument feasibility.

The first task would involve coordinating with the various commands and agencies that would be involved in the eventual use of a Global Hawk in support of tropical cyclone forecasting. These groups are broadly categorized as:

- Operational USAF and USN weather commands and civilian weather facilities (NOAA/NWS);
- Science organizations;
- Operational reconnaissance commands;
- Civilian organizations.

1. Operational Weather Commands (DoD and NOAA)

The primary operational USAF and USN commands are organized under the U.S. Pacific Command (USPACOM) and include the JTWC, Naval Meteorology and Oceanography Command installations in Japan, USAF 17th Operational Weather Squadron (OWS) at Hickam AB, HI, weather squadrons at Kadena AB, Okinawa, Japan, Yokota AB, Japan, and Andersen AB, Guam. Furthermore, the NOAA/NWS Central Pacific Hurricane Center, and Forecast Offices in Hawaii and Guam would be involved to define operational requirements in support of their operations. Additionally, coordination with the Fleet Numerical Meteorology and Oceanography Center (FNMOC), Monterey, CA would be required as observations collected for definition of model initial conditions are used at FNMOC. There is also a need to coordinate with other tropical cyclone programs in the western North Pacific, which include the DOTSTAR program in Taiwan and the program conducted by the Japan Meteorological Agency (JMA).

2. Science Organizations

Concurrent with coordination of the operational weather commands, collaboration is desired with several USN, NOAA, and NASA laboratories in which significant experience exists with respect to the use of reconnaissance data for initialization of numerical models. The objective of the coordination with science laboratories and agencies is to identify the scientific basis under which the Global Hawk operation will be undertaken. Specifically, a direct collaboration should be established with the Naval Postgraduate School (NPS) and the Naval Research Laboratory (NRL), Monterey CA. Additional collaboration should be established with NASA/Goddard Space Flight Center (GSFC), at which the lead investigators for the GRIP and HS3 reside. Finally, collaboration with the NOAA/AOML will be established to connect with the operational tropical cyclone reconnaissance that is conducted over the tropical North Atlantic in support of the NHC.

3. Operational Reconnaissance Commands

Based on the above, the operational requirements for tropical cyclone reconnaissance and the scientific basis for those requirements are established. In tandem

with those specifications, the operational reconnaissance commands must define the capabilities and feasibility associated with meeting the operational requirements. This will be the objective of the coordination with operational reconnaissance commands.

4. Civilian Organizations

As part of the existing development of tropical cyclone reconnaissance by the Global Hawk or manned aircraft, several civilian institutions are developing a dropwindsonde capability for the Global Hawk. Since it is anticipated that the primary observation platform for use in TC reconnaissance over the WPAC by a Global Hawk will be deployment of dropwindsondes, there is a need to collaborate with the primary developers of such systems. The National Center for Atmospheric Research (NCAR) is a National Science Foundation sponsored facility in Boulder, CO. The development of a mini-dropwindsonde system for the Global Hawk has been undertaken at NCAR and successfully tested in several missions over the eastern North Pacific. A second dropwindsonde system is being developed under sponsorship of the Office of Naval Research (ONR) for potential use with a Global Hawk. This system is being developed at Yankee Environmental Systems (YES) Inc.

C. MANPOWER

The manpower required for TC reconnaissance experiments can be much different than ongoing operational reconnaissance missions. The goal of this study is to assess the requirements needed for the Global Hawk on an as-needed basis, so the manpower requirements will be more closely related to those of TC experiments, but on a smaller scale. Some staff support will be required year-round, to allow for maintenance, training, and overhead. When determining the manpower, the locations and number of bases are a factor. In this case, the Global Hawk aircraft will likely be stationed at one base for TC reconnaissance, and that base would reside in the WPAC. If the sole purpose of the aircraft will be for TC reconnaissance and no other missions, operational maintenance can be kept at a minimum. If combined with other reconnaissance missions, more work/manpower could be required. This may also change the manning requirement from deployment teams to permanent party. In a similar comparison, a study conducted by

Whitney, et. al (2005) showed that the majority of the civilian manning would be for maintenance, followed by aircrew. These two categories comprised approximately 80% of the manpower (Figure 35). Of the civilian members that make up the majority of the manning, it is estimated that 75% would be contractors.

Civilian Skill Sets

Liaison with industry suggested these skill sets are obtainable ...

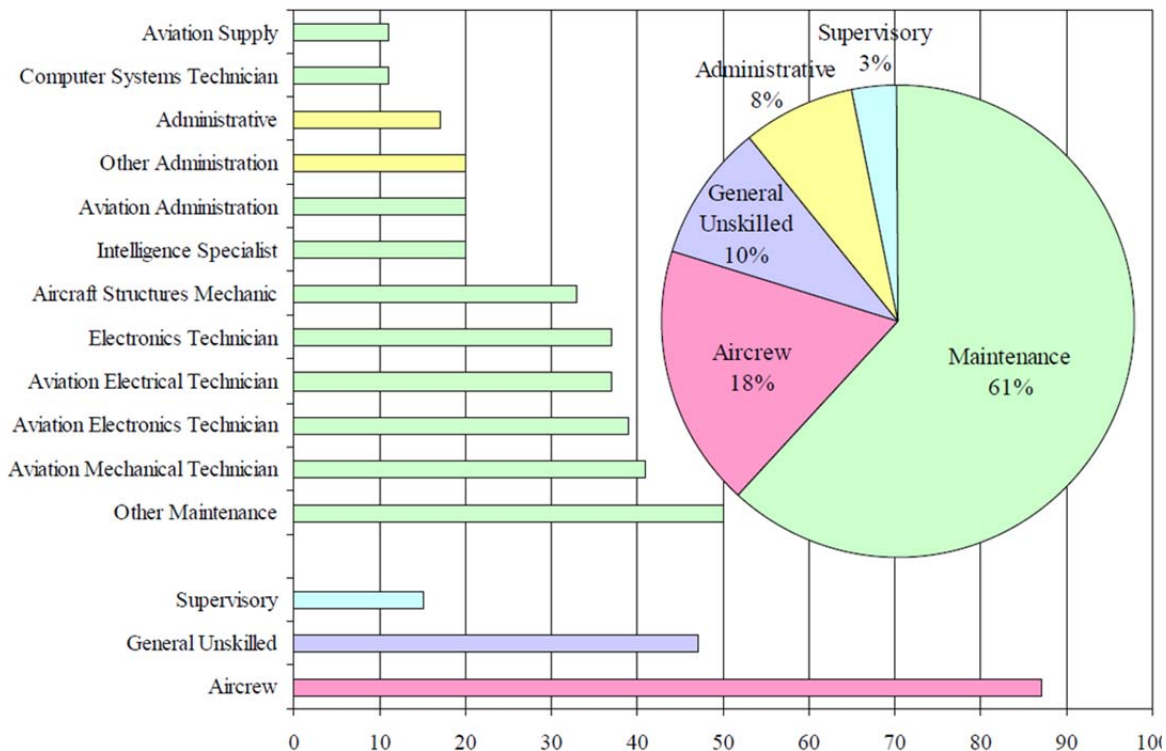


Figure 35. Civilian skill sets needed to maintain MQ-4C version of the Global Hawk for ISR missions. (Whitney, Bradley & Brown, 2005)

D. OPERATIONAL CONSTRAINTS

The objective of TC reconnaissance experiments has been to strategically utilize the UAS to better document areas of the storm that are either impossible or impractical to observe. The UAS data should provide improved initialization of forecast models, and invaluable ground truth for satellite and aircraft remote sensor measurements.

One of the operational constraints that can affect unmanned aircraft for TC reconnaissance experiments is access to airspace. Reconnaissance aircraft require “unconstrained” access to the national airspace system (NAS) to complete their missions (Cox, et al, 2006). The Federal Aviation Administration (FAA) requires Certificates of Waiver or Authorization (COA). These COAs do remove some flexibility in operations and planning. For example, COAs have limited number of waypoints, and in NOAA’s demonstration with the Altair UAV, they noted that the approval of flight plans was challenging. A primary mission plan and a backup are required.

Special use airspace can also present other constraints. Some areas request payment for their services in designating space. Many require knowing and approving the flight plans prior to testing.

Another operational constraint is command and control (C2). Tropical cyclone missions require that the C2 system respond to input from a payload system (to track dynamic phenomena), another UAV (for coordinated flight), or any other non-human source (such as satellite weather data). (Note: the use of GPS satellite data is not meant to be included with this need for "satellite data"). Effective manned TC reconnaissance missions have utilized 3-4 aircraft at various heights and distances from the core of the TC. The increased capability of a Global Hawk allows for a single aircraft to cover a region over which multiple manned aircraft were required. The coordination between various agencies requires much planning and during operations, communications among the teams must be clear, and consistent. Policies among different agencies can vary with regards to how operations are conducted. Depending on the locations, certain data may be restricted by types or the time of day. For example, some observations are limited by the amount of daylight, while some types of bandwidth cannot be transmitted over military bases. It is important to also be aware of any GPS jamming that may be occurring.

Depending on what aspects are being studied, range and endurance can vary with each mission. During reconnaissance over the WPAC, a lot of observational time is lost in transit from the base to the storm. In T-PARC/TCS-08, the C-130J flew 4 hours before reaching the storm. That would leave only four observational hours. Typical TC

experiments are on scales of weeks and months. The analysis of one TC could last 14 or more days and require a range of 10000 nautical miles.

Operations during TC reconnaissance can be complex. From initial planning to lessons learned, the goal is always to increase understanding in the most effective way possible. Observations have been proven to improve initializations, and those improved model simulations and forecasts lead to better forecasting skill. The technology is increasing and more data is becoming available. The lower levels of the storm are being studied with the hopes of further improvement in efficiency and accuracy. Technology has now advanced enough to potentially present the entire storm structure. With aircraft the Global Hawk, the constraints of endurance to monitor the evolutionary processes and that of deploying dropwindsondes at the upper levels will be removed.

E. GLOBAL HAWK INSTRUMENT SUITE

To adequately meet the mission goals of TC reconnaissance, a minimum requirement for observing capability is a dropwindsonde system on the Global Hawk. In this section, the AVAPS dropwindsonde system is defined. Additional instruments that remotely-sense the atmosphere are also defined.

1. Advanced Vertical Atmospheric Profiling System (AVAPS)

The Advanced Vertical Atmospheric Profiling System (AVAPS) is the dropwindsonde system for the Global Hawk. The Global Hawk dropwindsonde is a miniaturized version of standard RD-93 dropwindsondes based largely on recent MIST driftsondes deployed from balloons. The dropwindsonde provides vertical profiles of pressure, temperature, humidity, and winds. Data from these sondes are transmitted in near real-time via Iridium or Ku-band satellite to the ground-station, where additional processing will be performed for transmission of the data via the Global Telecommunications System (GTS) for research and operational use. The dispenser is located at the rear of the Global Hawk tail and is capable of releasing up to 88 sondes in a single flight (Figure 36).

2. Hurricane Imaging Radiometer

Based off the Stepped Frequency Microwave Radiometer (SFMR), an instrument that is flown on the WC-130J and WP-3 aircraft, HIRAD is a multi-frequency, hurricane imaging, interferometric single-pol passive C-band radiometer, operating from 4 GHz to 7 GHz, with both cross-track and along-track resolution that measures strong ocean surface winds through heavy rain from an aircraft or space-based platform. A one-dimensional thinned synthetic aperture array antenna is used to obtain wide-swath measurements with multiple simultaneous beams in a push-broom configuration. Its swath width is approximately 60 degrees in either direction. There are two products: rain rate and wind speed.

3. High Altitude Imaging Wind and Rain Airborne Profiler (HIWRAP)

The HIWRAP is a dual-frequency radar (Ka- and Ku-band), dual-beam (300 and 400 incidence angle), conical scan, solid-state transmitter-based system, designed for operation on the high-altitude (20 km) Global Hawk UAV. Conical scanning by the HIWRAP provides a map of the 3-dimensional winds and precipitation within hurricanes and other severe weather events.

4. Scanning High-Resolution Interferometer Sounder (S-HIS)

The Scanning High-resolution Interferometer Sounder (S-HIS) is a scanning interferometer that measures emitted thermal radiation at high spectral resolution between 3.3 and 18 microns. The measured emitted radiance is used to obtain temperature and water vapor profiles of the Earth's atmosphere in clear-sky conditions. S-HIS produces sounding data with 2 kilometer resolution (at nadir) across a 40 kilometer ground swath from a nominal altitude of 20 kilometers onboard a NASA ER-2 or Global Hawk (Figure 36).

5. Cloud Physics Lidar

The Cloud Physics Lidar, or CPL, is a backscatter lidar designed to operate simultaneously at 3 wavelengths: 1064, 532, and 355 nm. The purpose of the CPL is to provide multi-wavelength measurements of cirrus, subvisual cirrus, and aerosols with

high temporal and spatial resolution. From the fundamental measurement, various data products are derived, including: time-height cross-section images; cloud and aerosol layer boundaries; optical depth for clouds, aerosol layers, and planetary boundary layer (PBL); and extinction profiles.

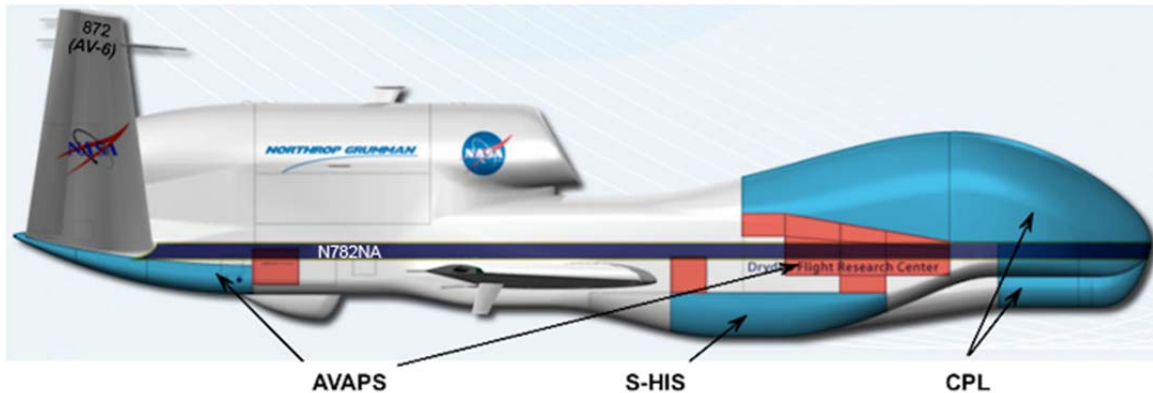


Figure 36. HS3 Environmental Payload contained on the NASA Global Hawk used for monitoring the environment of a TC.

6. High Altitude Monolithic Microwave integrated Circuit (MMIC) Sounding Radiometer

The High Altitude Monolithic Microwave Integrated Circuit (MMIC) Sounding Radiometer (HAMSR) is a microwave atmospheric sounder developed by the Jet Propulsion Laboratory (JPL) under the NASA Instrument Incubator Program. Operating with 25 spectral channels in 3 bands (50–60 GHz, 118 GHz, 183 GHz), it provides measurements that can be used to infer the 3-D distribution of temperature, water vapor, and cloud liquid water in the atmosphere, even in the presence of clouds. HAMSR is mounted in payload zone 3 near the nose of the Global Hawk.

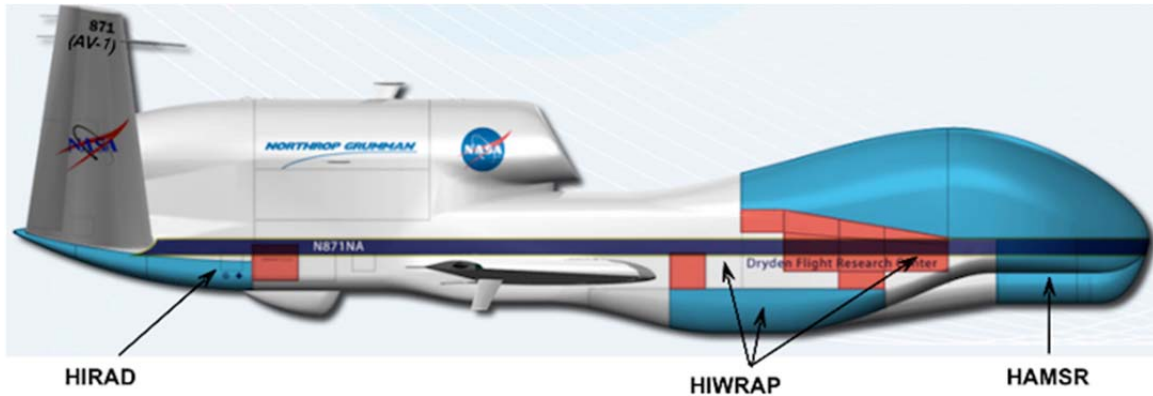


Figure 37. HS3 Over-Storm Payload contained on the NASA Global Hawk used for monitoring the inner core of a TC.

F. OPERATIONS

To observe the environmental and inner-core vertical structure from the upper levels of the storm, the dropwindsondes would be deployed from the Global Hawks. The AVAPS system developed by NCAR aboard the HS3 Environmental Global Hawk could be used to provide this capability. This could also be achieved by retrofitting another USN/USAF Global Hawk with a dropwindsonde system. Again, the ability to deploy dropwindsondes is a minimum requirement for operations. Because the Global Hawk can provide near-instantaneous mapping of the entire inner-core hurricane surface wind field and rain structure.

During the mission, the aircraft and their data would be controlled and monitored by coordination centers throughout the Pacific. The aircraft could be flown out of Guam or Japan with its coordination taking place at either Andersen AB, or Yokota AB, respectively. These bases would provide the necessary infrastructures for safe take-off, location of dropwindsondes, and landings depending on the location of the TC. Operations, such as flight planning and deployments, would be headquartered at the Naval Postgraduate School in Monterey, CA. The research team in Monterey would be in position to provide the scientific support needed to conduct operations.

If the NASA Global Hawk is used, operations would be monitored and controlled by the operators at the Dryden Flight Research Center at Edwards AFB CA. However, if a USAF/USN Global Hawk is used, the operational control would be by the respective command structure.

These mission characteristics comprise the framework needed to incorporate the Global Hawk into JTWC and DoD support missions throughout the WPAC. Through coordination with the operational weather commands and scientific organizations, the roadmap can be developed, operations can be successfully conducted and the requirements of reducing uncertainty can be achieved. The analysis of the new data will have to be assessed, and from these assessments, the value of these observations can be determined.

V. COMPARATIVE ANALYSIS

A challenge for any operational TC reconnaissance program is to provide for the most effective observing strategy while minimizing costs. This chapter will examine some of the estimated costs associated with TC reconnaissance over the WPAC, and the potential for the Global Hawk to enhance and further optimize the use of these resources.

A. FUEL COST

As mentioned in the previous chapters, TC reconnaissance over the Atlantic is performed by a fleet of WC-130J aircraft that operate from Keesler AFB, MS. One of the largest costs associated with the aircraft operation is the amount of fuel required, which is related to the aircraft range and the relative location of TC activity. Over the WPAC, the area coverage of TC activity is much larger than over the Atlantic. The aircraft used during the T-PARC exercise were based at various locations throughout the WPAC to enable the aircraft with shorter range to reach regions of TC activity. The smaller jets (Falcon and Gulfstream) have an average rate of fuel consumption of 300–400 gal hr⁻¹. The larger planes (P-3 and WC-130J) consume roughly 700 gal hr⁻¹ (Table 3). The larger planes operated from Andersen AB, Guam and traveled the longest distances to reach the westward moving storms. Based on the number of flight hours flown during the two-month period of T-PARC/TCS-08, the number of gallons used would equate to roughly 42,000 gallons by the jets, and 276,500 gallons for the larger planes.

Aircraft	Duration (hours)	Altitude (feet)	Range (nm)	Fuel Consumption (gal h ⁻¹)
Gulfstream	8	40000	6000	444
P-3	13	10000	2500	700
Global Hawk	30	65000	11000	70

Table 3. Comparison of some characteristics of aircraft used for operational TC reconnaissance.

B. SATELLITES

Currently, data from geostationary and polar-orbiting satellites are used to monitor TC locations and characteristics over the WPAC. The NOAA FY 2013 Budget Summary identified a request for \$9.7 million to support the Suomi National Polar-orbiting Partnership (Lubchenco, 2012). The Suomi NPP is the first NASA satellite mission to address the challenge of acquiring a wide range of land, ocean, and atmospheric measurements for Earth system science while simultaneously preparing to address operational requirements for weather forecasting (Lubchenco, 2012). Note that this is not the cost of the satellite or its launch. These funds are used to procure IT capabilities to process and distribute the data. The cost of building satellites can range from the hundreds of millions to a billion dollars. For the purpose of TC reconnaissance, processing satellite data is a major cost, but necessary as the data represent the only measurements of TC characteristics. However, many satellite systems are operating beyond their projected lifetime. Therefore, costs of satellite-based TC reconnaissance will rise dramatically or the capability to remotely-sense TC characteristics will be lost.

In this section, the costs associated with a pilot program for use of a Global Hawk for TC reconnaissance over the WPAC are discussed. The proposed pilot program is designed to operate for two months during the peak period of TC activity, which is late August through late October. The estimated number of flight hours is 300. Because the Global Hawk and its associated observing system has not operationally been used in the WPAC environment, the concurrent use of two WC-130J aircraft is considered as a measure for obtaining ground truth data to compare with the Global Hawk data. Additionally, specification of the Global Hawk capabilities are defined in Chapter V.

The Global Hawk consumes fuel at a rate of 70 gal hr^{-1} , and depending on the location of the target TC, the Global Hawk could remain on station for over 20 hours. Relative to the amount of data that can be recorded, this a significant cost savings compared to current methods of TC reconnaissance.

An estimated total cost for the two month pilot program is approximately \$6.5 million (Table 4). Several key assumptions are made in the analysis. One is that a

NASA Global Hawk would be used for the test program. A second assumption is that two dropwindsonde systems (AVAPS and YES) will be supported. A third assumption is that Andersen AB, Guam will be an available base of operations. However, there may be some issues related to adequate weather condition for optimum Global Hawk activities for Guam. Once operational, reconnaissance with the Global Hawk would no longer require verification from manned aircraft, which could reduce the budget by one-third. It is important to remember that over the WPAC, an area that has over 180 ships, 2000 aircraft, 325,000 personnel, and averages of 31 TCs per year, there is no TC aircraft reconnaissance.

Activity	\$ Cost in millions
GH Operations	2.5
Site Support (i.e., Guam)	0.3
Project management	0.5
HIRAD support	0.4
AVAPS support	0.3
YES support	0.3
AVAPS drops (500 sondes @ \$800)	0.4
YES drops (500 sondes @ \$800)	0.4
Mission science (PI) support	0.3
Science team support	0.5
Subtotal	5.9
Reserves (~10%)	0.6
Total	6.5
53rd Weather Reconnaissance Squadron, two WC-130J for 2 months, 300 hours plus aircrew	3
500 WC-130J dropwindsondes = \$400K	0.4

Table 4. Sample budget of a demonstration Global Hawk experiment. (Dr. Peter Black, National Research Laboratory.)

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7
Retrofitting cost	4,700,000						
Maintenance (Overhaul, contracts, labor & parts)		850,000	850,000	850,000	850,000	850,000	850,000
Fuel @ \$ 4.50		364,000	364,000	364,000	364,000	364,000	364,000
Training	300,000	300,000	300,000	300,000	300,000	300,000	300,000
Crew Cost	741,274	1,482,547	1,482,547	1,482,547	1,482,547	1,482,547	1,482,547
Overhead	202,480	202,480	202,480	202,480	202,480	202,480	202,480
Overtime		325,000	325,000	325,000	325,000	325,000	325,000
Scheduled PDM ?							
Sat. Commun.		476,000	476,000	476,000	476,000	476,000	476,000
Range Operations		150,000	150,000	150,000	150,000	150,000	150,000
Ground Control Station Maintenance & Upgrades		350,000	350,000	350,000	350,000	350,000	350,000
Payload Development/Instrumentation	1,200,000						
Cons.		167,000	167,000	167,000	167,000	167,000	167,000
Ground Control Station Comm Systems Maint.		150,000	150,000	150,000	150,000	150,000	150,000
Total	7,143,754	4,817,027	4,817,027	4,817,027	4,817,027	4,817,027	4,817,027

Table 5. A distribution of costs associated with ongoing operational use of the Global Hawk for TC reconnaissance

C. UNMANNED AERIAL SYSTEM: GLOBAL HAWK

To assess the value of the data obtained from the operation of the Global Hawk over the WPAC, studies of the impact of TC data on forecasts from operational numerical weather prediction systems should be undertaken. The studies will examine the impact of the data on initial conditions used in each model. Data-denial experiments will be conducted in which parallel operations are implemented such that one contains the Global Hawk data and the other does not. The forecasts will be assessed in lieu of the accuracy of the TC track and intensity. It may be that to obtain an adequate sample size, the pilot program should be conducted over successive TC seasons. Assuming a successful pilot program, an operational TC reconnaissance program would involve other ongoing factors (Table 5). In this analysis, it is assumed that an operational Global Hawk would be retrofitted with one dropwindsonde system (i.e., AVAPS or YES). This cost is contained in the first year of the program. Once the Global Hawk is retrofitted with the required instrumentation, the yearly operational costs drop substantially. Again, this is also an

estimate, but presents the reader with an idea of what factors determine such costs and provides an estimate of the value of Global Hawk to TC reconnaissance.

As interest in UAS for TC reconnaissance continues to grow, so will the options to conduct operations. The Global Hawk is one of the aircraft in the Q-4 series of HALE UAVs designed by the Northrop Grumman Corporation. The current Global Hawk enterprise consist of four complimentary systems, or Blocks. The Block 10 is the initial airframe after the DARPA technology demonstration. Block 20 is the first production version, and was released in August 2006. Block 30 added signals intelligence (SIGINT) capability, and the Block 40 is currently in the final development stages.

The Global Hawk airframe falls under Northrop Grumman's Q-4 Enterprise. The Q-4 Enterprise consists of any unmanned aircraft system, based on the Global Hawk airframe, that is equipped with a tailored sensor suite that depends on the user's requirement. The U.S. Air Force flies the RQ-4, a HALE UAS with ISR capability, which provides near-real-time high resolution imagery of large geographical areas for both day and night operations. The U. S. Navy flies the MQ-4C version known as the Broad Area Maritime Surveillance (BAMS) program. The BAMS UAS uses a maritime derivative of the RQ-4 Global Hawk equipped with a 360 degree Multi-Function Active Sensor (MFAS). The U.S. Navy procured two Block 10 Global Hawks for the Global Hawk Maritime Demonstration (GHMD) program from the U.S. Air Force, and is using them to help define concept of operations for maritime surveillance. Scientific organizations, such as NASA have partnered with Northrop Grumman to demonstrate HALE capability for future customers and experiments for the environmental science community to include NOAA, NASA, Department of Energy, and universities. The NASA Global Hawk has participated in experiments including Global Hawk Pacific (GloPac) 2010, Genesis and Rapid Intensification Processes (GRIP), and the Hurricane and Severe Storm Sentinel Project (HS3).

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VI. RECOMMENDATIONS

Although the primary manned-aircraft platforms provide for the capability to measure many aspects of the environment in and around a TC, they have two primary limitations. Manned-aircraft duration is limited such that at most 6–8 h are available for the aircraft to be on station and collecting data. The observation time can be as little as 3 h if the ferry time to the storm is long. The primary manned-aircraft platforms defined above are also limited in terms of the maximum altitude at which they can gather observations. In a non-TC environment, the WC-130J may operate around 30,000 ft. However, in the storm environment, the aircraft operate at 10,000 ft due to severe icing conditions at the higher altitudes. Because the typical vertical extent of a TC is about 50,000 ft, the dropwindsonde observations deployed from the WC-130J and WP-3D only measure the lowest portion of the storm structure and the environment. While dropwindsondes observations from the G-IV are obtained from a flight level of approximately 40,000 ft, these observations are in remote regions away from the TC as the G-IV does not fly over the TC. These limitations reduce the utility of the observations in specifying the full three-dimensional structure of the storm in the initial conditions of a numerical model.

To address the objectives of increased forecast accuracy and reduced forecast uncertainty of TCs over the western North Pacific, the use of a Global Hawk to provide *in situ* measurements of improved initial conditions of model integrations is proposed. The use of a Global Hawk would remove both limitations related to use of the manned aircraft and increase the utility of the observations for defining the storm wind radii and structure for real time operational warnings, and as model initial conditions.

A. WORKSHOP

To facilitate the discussion and refine the requirements needed to incorporate the Global Hawk into TC reconnaissance missions over the WPAC, a workshop hosted and supported by the Consortium for Robotics and Unmanned Systems Education and Research (CRUSER) is proposed. The mission of CRUSER is to provide a collaborative

environment and community of interest for the advancement of unmanned systems education and research endeavors across the Navy, Marine Corps and Department of Defense. An innovative workshop on the application of this unmanned system would provide the resources and support needed to facilitate the final stages of planning, and transition to operations. This workshop will also bring key personnel and decision makers from USPACOM, Air Force operators, JTWC, USAF 17th Operational Weather Squadron, and NASA

B. DEMO PROJECT

The JTWC was created in the wake of Typhoon Cobra on 18 December, 1944, the largest naval disaster in U.S. history (790 lives lost). It was tasked to provide TC warnings for the North West Pacific Ocean, South Pacific Ocean and Indian Ocean for U.S. DoD interests, as well as U.S. and Micronesian civilian interests within the command's area of responsibility (AOR). All branches of the U.S. DoD and other U.S. government agencies are supported by the products of the JTWC, for the protection of primarily military ships and aircraft as well as military installations jointly operated with other countries around the world.

Per USPACOM Inst 0539.1, PACAF is supported commander for TC reconnaissance. Manned flights discontinued in 1987 in favor of satellite reconnaissance. However, satellite capabilities, such as those from NPOESS, and the Defense Weather Satellite System (DWSS) are failing, while the uncertainty of those beyond their lifecycles continues to rise. In addition to failing satellites, budget constraints, along with the DWSS MIS-43 payload cancellation have led the dependence of commercial OSVW use by the JTWC. The NASA Global Hawk is a proven resource that has the potential to not only complement the OSVW, but can provide increased coverage over TCs over the WPAC, a capability that has been gapped over the last 25 years.

It is recommended that USPACAF and JTWC leverage the NASA Global Hawk to conduct their demonstration project over the western North Pacific. This demonstration as outlined in the previous chapter would provide data needed to assess the added value of deploying dropwindsondes at the upper levels. Once the benefits are

determined and weighted, it is recommended that the results be briefed to USPACOM. Upon receiving this brief, it is recommended for USPACOM to approve or deny the incorporation of the Global Hawk as an operational unit for TC reconnaissance over the WPAC in support of JTWC.

C. CHANGES TO TC RECON PLANS

Once the benefits of using the Global Hawk for TC recon have been identified, assessed, and approved, the next step would be to incorporate the new procedures into the operational doctrine. Changes would involve dedicated aircraft to the WPAC. Inter-agency coordination and planning would now involve multi-national agreements. And the new doctrine would have to identify the value and standing operating procedures (SOPs).

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LIST OF REFERENCES

- Chan, Johnny C-L., 1986: Supertyphoon Abby—an example of present track forecast inadequacies. *Wea. Forecasting*, **1**, 113–126.
- Chou, Kun-Hsuan, Chun-Chieh Wu, Po-Hsiung Lin, Sim D. Aberson, Martin Weissmann, Florian Harnisch, Tetsuo Nakazawa, 2011: The impact of dropwindsonde observations on typhoon track forecasts in dotstar and t-parc. *Mon. Wea. Rev.*, **139**, 1728–1743.
- Cione, J., 2012: Module description GALE UAS/eyewall module.
[http://www.aoml.noaa.gov/hrd/HFP2012/3_GALE_UAS.pdf]
- Cox, T., Ivan Somers, David J. Fratello, 2006: Earth observations and the role of UAVs: a capabilities assessment. v. 1.1, 29–33.
- Darack, E/Weatherwise, 2012 (Mar-Apr): UAVs: the new frontier for weather research and prediction.
[<http://www.weatherwise.org/Archives/Back%20Issues/2012/March-April%202012/UAVs-full.html>]
- Elsberry, R. L., and P. A. Harr, 2008: Tropical cyclone structure (TCS2008) field experiment: science basis, observational platforms, and strategy. *Asia-Pacific J. Atmos. Sci.*, **44**, 122–143.
- Emanuel, K. (2007), Comment on “Sea-surface temperatures and tropical cyclones in the Atlantic basin” by Patrick J. Michaels, Paul C. Knappenberger, and Robert E. Davis, *Geophys. Res. Lett.*, **34**, L06702,
- Goerss, J, S., and R. A. Jeffries, 1994: Assimilation of synthetic tropical cyclone observations into the navy operational global atmospheric prediction system. *Wea. Forecasting*, **9**, 557–576.
- Goerss, J, S., C. R. Sampson, J. M. Gross, 2004: A history of western north pacific tropical cyclone track forecast skill. *Wea. Forecasting*, **19**, 633–638.
- Goerss, James S., 2009: Impact of satellite observations on the tropical cyclone track forecasts of the navy operational global atmospheric prediction system. *Mon. Wea. Rev.*, **137**, 41–50.
- Halverson, J. B., J. Simpson, G. Heymsfield, H. Pierce, T. Hock, L. Ritchie, 2006: Warm core structure of hurricane erin diagnosed from high altitude dropwindsondes during camex-4. *J. Atmos. Sci.*, **63**, 309–324.

- Harnisch, Florian, Martin Weissmann, 2010: Sensitivity of typhoon forecasts to different subsets of targeted dropwindsonde observations. *Mon. Wea. Rev.*, **138**, 2664–2680.
- Harr, P. A., D. Anwender, S. C. Jones, 2008: Predictability associated with the downstream impacts of the extratropical transition of tropical cyclones: Methodology and a case study of Typhoon Nabi (2005). *Mon. Wea. Rev.*, **136**, 3205–3225.
- Holland, G.J., 1983: Tropical cyclone motion: environmental interaction plus a beta effect. *J. Atmos. Sci.*, **40**, 328–342.
- Jones, S. C., and Co-authors, 2003: The extratropical transition of tropical cyclones: Forecast challenges, current understanding, and future directions. *Wea. Forecasting* **18**, 1052–1092.
- Justice, E., 2012: HS3 hurricane intensity change and internal processes [http://espo.nasa.gov/missions/hs3/content/HS3_Hurricane_Intensity_Change_and_Internal_Processes]
- Knaff, John A., Charles R. Sampson, Mark DeMaria, 2005: An operational statistical typhoon intensity prediction scheme for the western north pacific. *Wea. Forecasting*, **20**, 688–699.
- Lin, Po-Hsiung, 2006: OBSERVATIONS: The first successful typhoon eyewall-penetration reconnaissance flight mission conducted by the unmanned aerial vehicle, aerosonde. *Bull. Amer. Meteor. Soc.*, **87**, 1481–1483.
- Lin, Po-Hsiung, Cheng-Shang Lee, 2008: The Eyewall-Penetration Reconnaissance Observation of Typhoon Longwang (2005) with Unmanned Aerial Vehicle, Aerosonde. *J. Atmos. Oceanic Technol.*, **25**, 15–25.
- Lorenz, Edward N., 1963: Deterministic nonperiodic flow. *J. Atmos. Sci.*, **20**, 130–141.
- Lubchenco, J., 2012: NOAA FY 2013 budget summary, program support, 180.
- Reynolds, C. A., M. S. Peng, and J.-H. Chen, 2009: Recurving tropical cyclones: singular vector sensitivity and downstream impacts. *Mon. Wea. Rev.*, **137**, 1320–1337.
- Schultz, B, 2009: Tropical Cyclone Conference. [Available online at <http://www.docstoc.com/docs/52191999/TROPICAL-CYCLONE-CONFERENCE-29-APR-2009>.]

- Uhle, W.W., 2009: Goals for Tropical Cyclone Forecasting. Ser: **J33**/#002, 3pp.
- Weissmann, M., F. Harnisch, C.-C. Wu, P.-H. Lin, Y. Ohta, K. Yamashita, Y.-H. Kim, E.-H. Jeon, T. Nakazawa, and S. Aberson, 2011: The influence of assimilating dropwindsonde data on typhoon track and midlatitude forecasts. *Mon. Wea. Rev.*, **139**, 908–920.
- Whitney, Bradley & Brown, Inc., 2005: Manpower requirements determination for new systems broad area maritime surveillance (BAMS) unmanned aerial vehicle (UAV). 73rd MORSS Conference 23 June 2005
- Wick, G./NOAA, 2011: WISPAR Winter Storms and Pacific Atmospheric Rivers. [<http://www.esrl.noaa.gov/psd/outreach/resources/handouts/wispar-2011.v2.pdf>]
- Wu, C. -C., Y.-H. Huang, and G. -Y. Lien, 2012: Concentric eyewall formation in Typhoon Sinlaku (2008)- Part I: assimilation of T-PARC data based on the ensemble Kalman Filter (EnKF). *Mon. Wea. Rev.*, **140**, 506–527.
- Wu, C.-C., and Coauthors, 2005: Dropwindsonde Observations for Typhoon Surveillance near the Taiwan Region (DOTSTAR): An overview. *Bull. Amer. Meteor. Soc.*, **86**, 787–790.
- Zipser, E., G. Heymsfield, 2011: NASA GRIP 2010 Overview of research flights. GRIP Science Meeting June 6–8, 2001. Los Angeles, CA

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